WATKINS-JOHNSON COMPANY

Title of Report RADC-TDR-63-172

Final Report

DEVELOPMENT OF S-BAND LOW-NOISE
PERIODIC PERMANENT MAGNET
TRAVELING-WAVE TUBE

By

B. P. Israelsen, J. H. Foster,
M. V. Purnell and F. T. Mauch

PUBLICATION REVIEW

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Watkins-Johnson Company
3333 Hillview Avenue
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W-J 63-604R4

19 March 1963

Contract No. AF 30(602)-2694

Prepared
for
Rome Air Development Center
Research and Technology Division
Air Force Systems Command
United States Air Force

Griffiss Air Force Base
New York

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ABSTRACT

Various methods of focusing a low-noise electron beam are described. Experimental results for reversed-field, combined straight and periodic fields, and shielded straight-field focusing are presented. Effective means for shielding a straight-field magnet and eliminating its transverse components on the axis were found. Developments in the low-noise tube which facilitated permanent-magnet focusing are described. These include the pin-seal input match, and a considerable reduction in the gun bulb and coupler diameters. Operation of the amplifier is simplified by the inclusion of a voltage divider network to furnish the helix and anode voltages. Performance of the completed amplifiers with regard to gain, noise figure, and phase is discussed.

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INTRODUCTION

This development program is concerned with the achievement of low-noise amplification in a focusing structure using periodic permanent-magnet focusing. The objective is to realize a noise figure of 3 db in such a device, with small-signal gain of 20 db, these performance figures to be realized over the frequency band 2.7-3.3 Gc. In addition, the phase stability of the tube should be ± 5 degrees.

The achievement of these goals entails two principal problems; first, the development of a focusing structure capable of yielding nearly perfect beam transmission, and secondly, modification of the tube design so as to yield substantially the same noise properties in the permanent magnet system as in a solenoid.

This report describes studies carried out to investigate various methods of beam focusing using permanent magnets, with emphasis on low-noise amplification. From these studies certain conclusions emerged, leading to the selection of a shielded straight-field magnet as the most appropriate for the present application. The program was given considerable impetus by significant developments in the tube and coupler, which are described in detail. The concluding portions of the report are taken up with a description of the end product resulting from the development, and a summary of the rf performance obtained.

DISCUSSION

A. Study Of Focusing Methods

The purpose of permanent-magnet focusing in a low-noise traveling-wave tube, as in any extended-beam microwave tube, is to provide confinement for the electron beam sufficient to enable its transmission from cathode through the helix to the collector. The configuration of field used to accomplish this is immaterial, so long as the noise performance suffers little or no degradation. Typically, in the past, low-noise tubes have required solenoids for their operation. Magnetic field values of 1000 gauss and higher are common. With the various types of permanent-magnet focusing available to the designer, limitations set by the characteristics of the material assert themselves. Thus the various types of Alnicos and ferrites each have certain field values and configurations to which they are best suited. This investigation comprised an effort to determine the type of magnet system, and geometry, best suited to low-noise amplification. Present technical feasibility, reproducibility, and eventual cost were all taken into consideration.

1. Reversed-Field Focusing

Alnico Magnets

Based on the criterion of having to focus an electron beam seven inches long, an Alnico 5 magnet designated as model R-10 was designed, to be used in pairs providing a single reversal. This magnet has the following characteristics:

Maximum OD at center	2 1/8 inches
OD at ends	1 15/16 inches
ID	1 1/4 inches
Length	4 5/8 inches
Weight	1.7 pounds

Six magnets of this type were obtained. The axial fields measured 600 gauss or slightly higher. Measurements of transverse field showed the maximum values for each magnet to be, respectively, 11, 22, 33, 40, 50, and 57 gauss. These values were reduced somewhat by remagnetizing

A magnet alignment capsule was designed and built to allow two of the R-10 magnets to be used in a reversed-field configuration. A pictorial drawing showing a cross-section of this assembly is shown in Fig. 1. One magnet is held fixed with respect to the capsule, while the other is movable with respect to the first, being held by two sets of three focusing screws each. Within the tube capsule, centered along the axis of the two magnets, is the tube and coupler assembly. The input coupler is a pin-match and the output coupler is a coupled helix. The tube capsule is positioned within the magnets for optimum beam focusing by means of focusing screws held in pole pieces (not shown in Fig. 1) on the magnet ends.

Figure 2 is a photograph of the coupler assembly designed to operate with the R-10 magnets. The laminated disc near the mouth of the tube capsule is a pole piece used to steepen the field reversal.

Figure 3 through 6 show field plots of two R-10 magnets in the assembly of Fig. 1. Figure 3 depicts the reversal with no pole piece at the reversal plane. A measure of the steepness of the reversal is the distance required for the field to change from a given positive value to the corresponding negative value. For present purposes, the field values used in computing the reversal distance are ± 400 gauss. In Fig. 3 the reversal distance is 0.83 inch. Figure 4 shows the effect of adding a steel pole piece at the reversal plane, the dimensions of the pole piece being indicated on the figure.

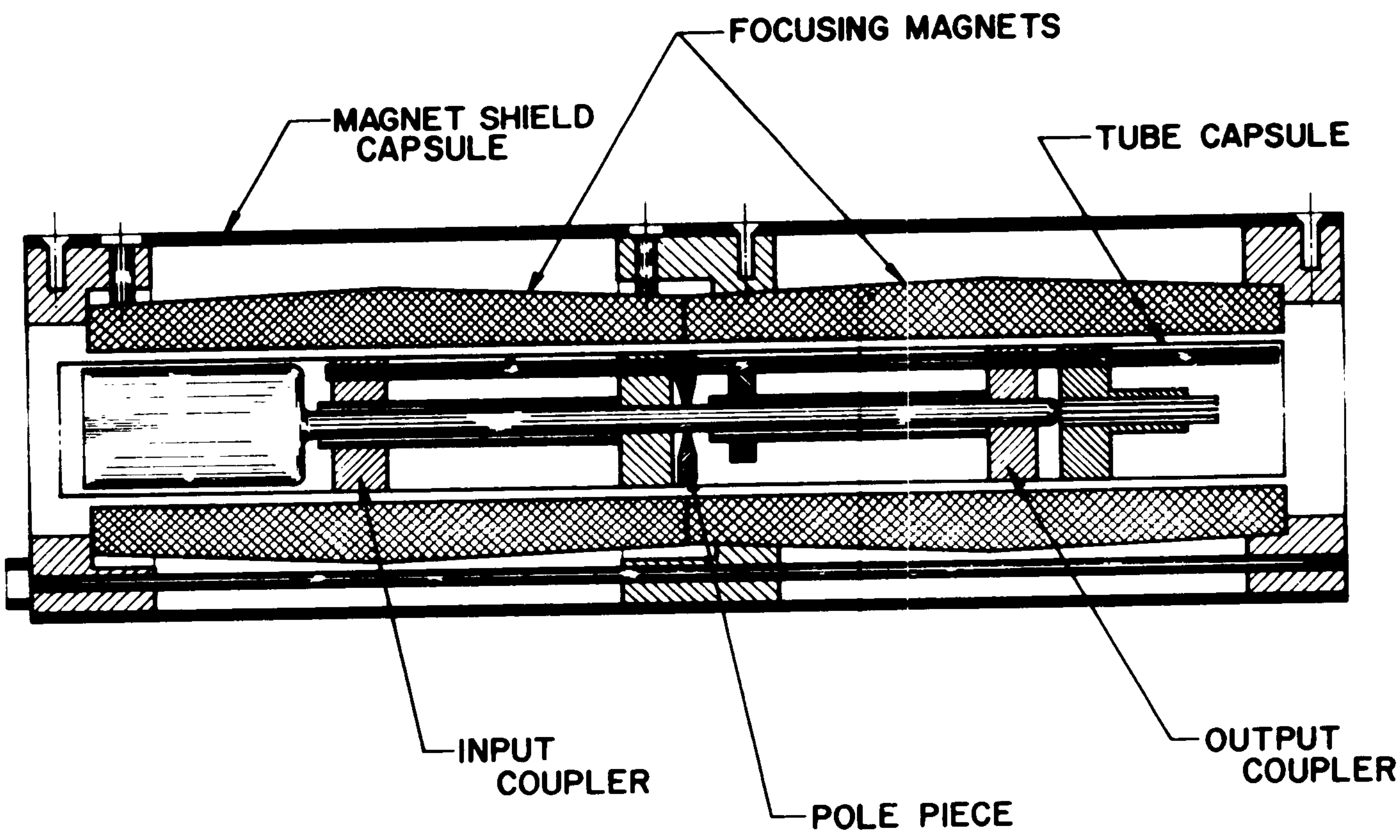

Fig. 1 - This sketch illustrates the method of supporting the two Alnico magnets to produce a single reversal. One magnet is held fixed with respect to the shield capsule, while the other is positionable with adjusting screws.

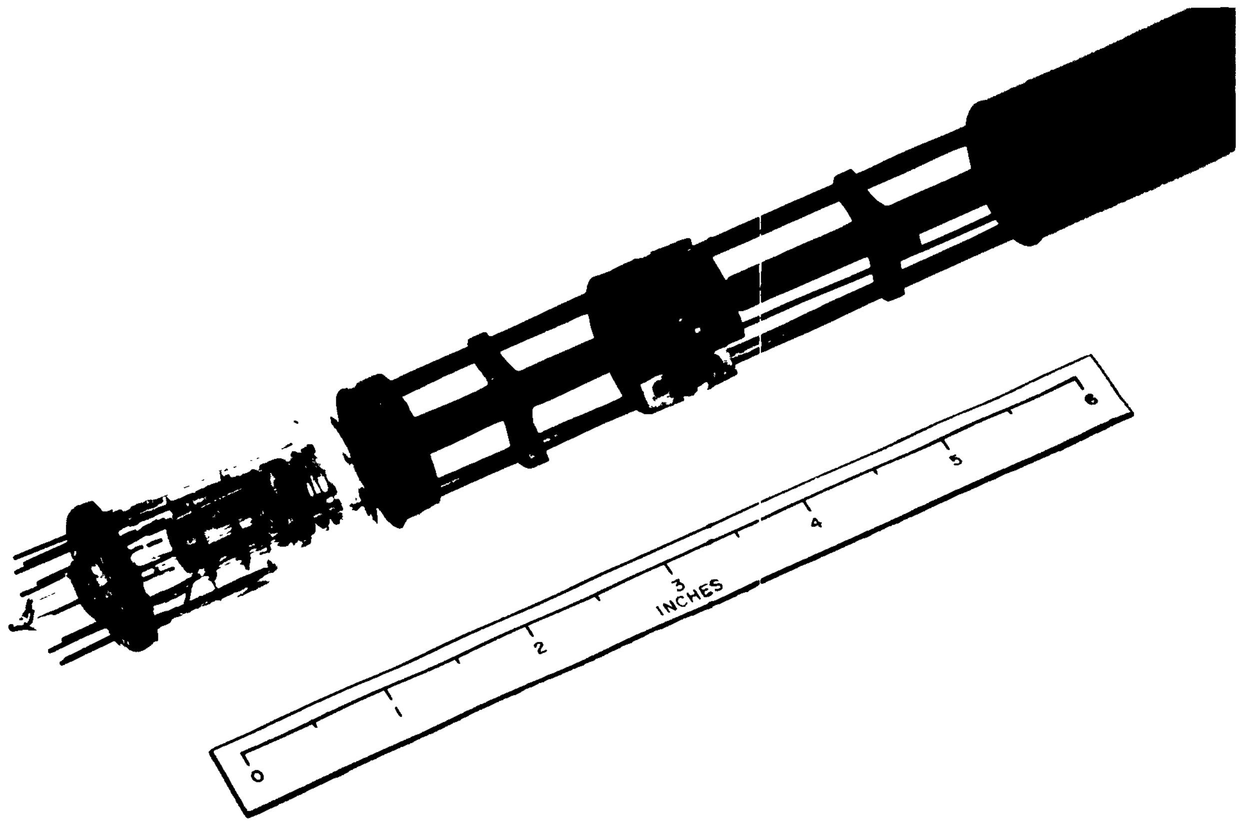

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Fig. 2 - Photograph showing a coupler designed for use with the reversed-field assembly of Fig. 1.

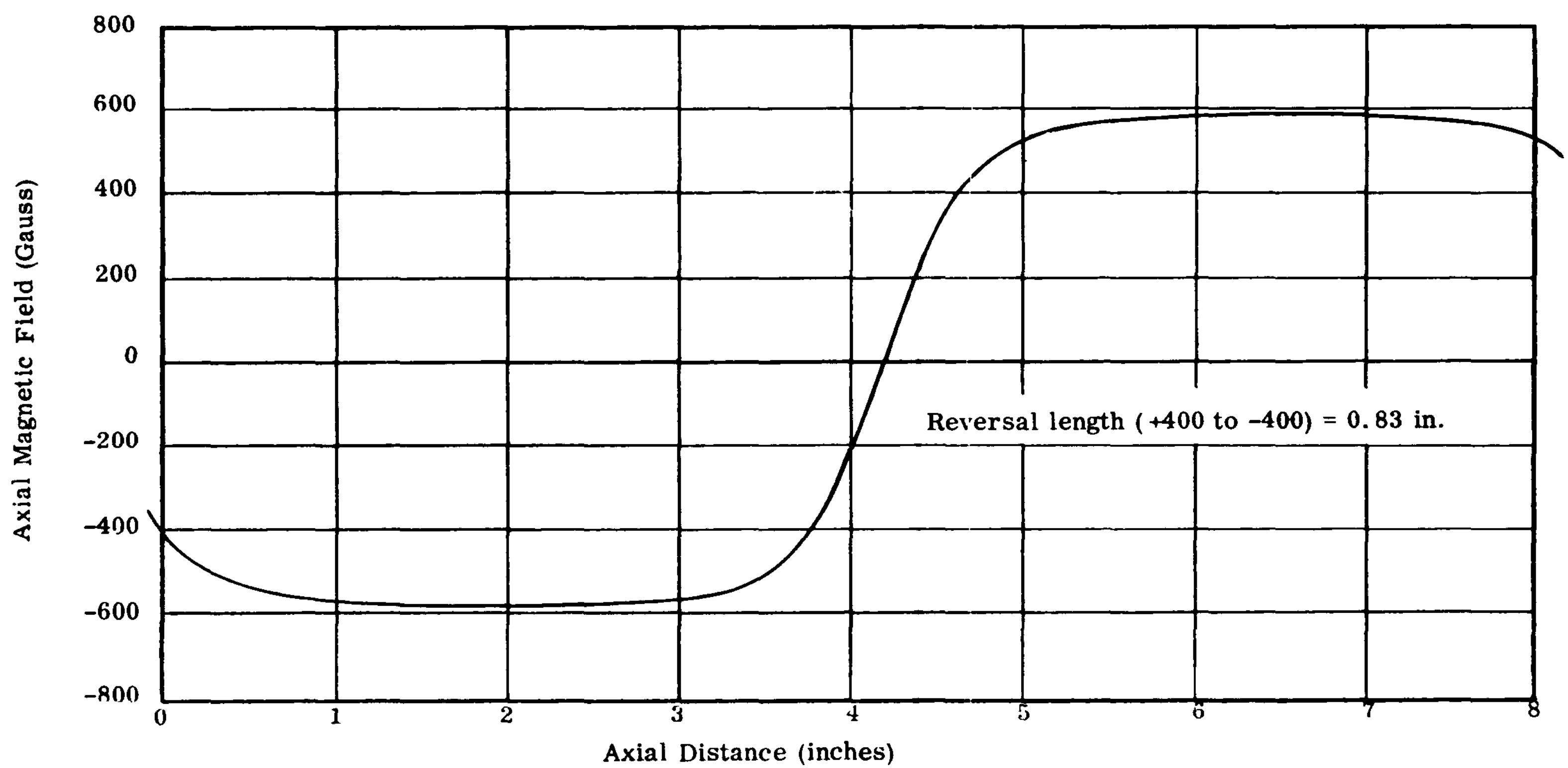

Fig. 3 - Reversed-field plot of two type R-10 Alnico magnets, with no pole piece or boosting magnets to steepen the reversal.

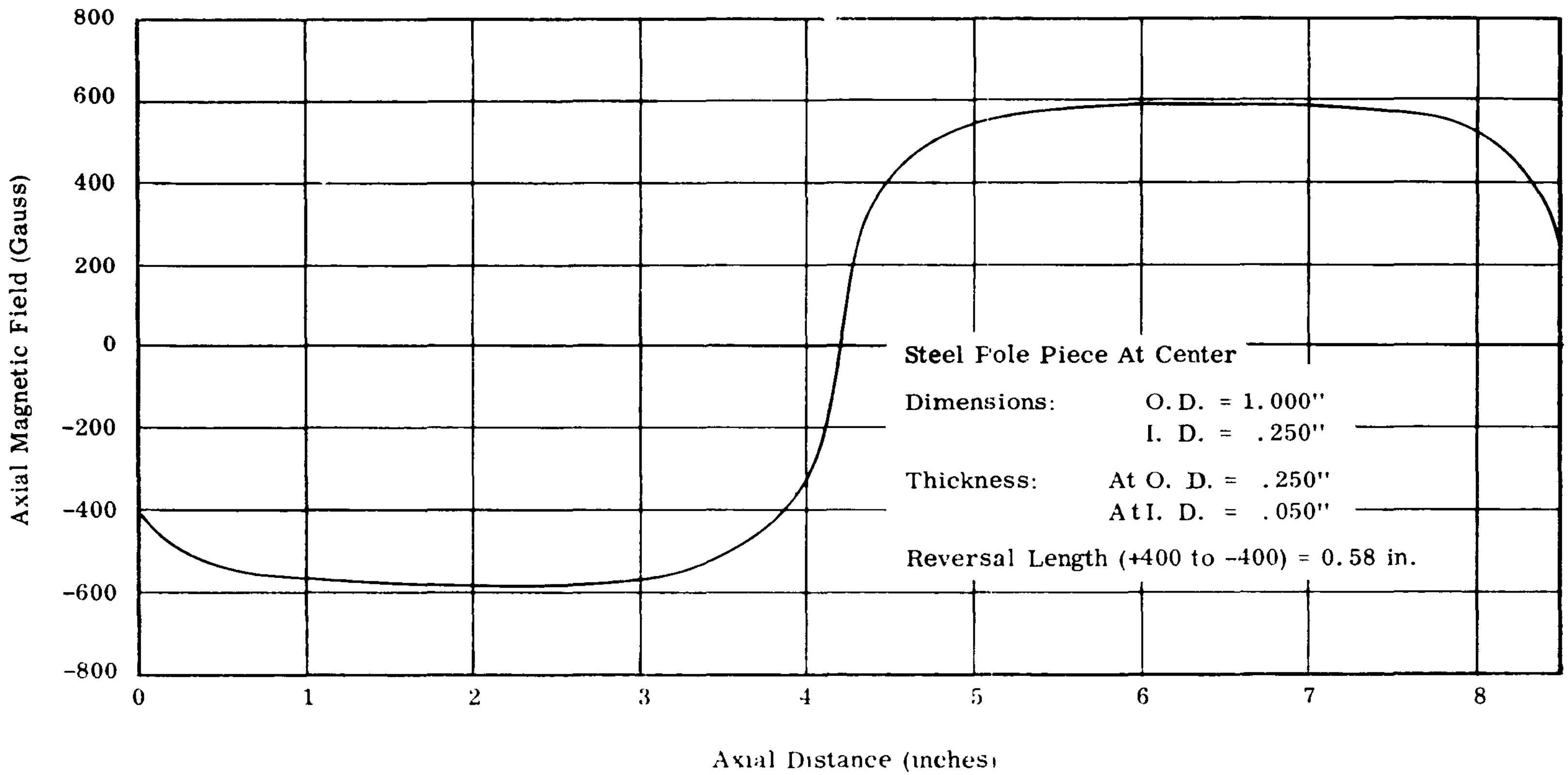

Fig. 4 - Reversed-field plot showing the steepening effect of adding a pole piece at the reversal plane.

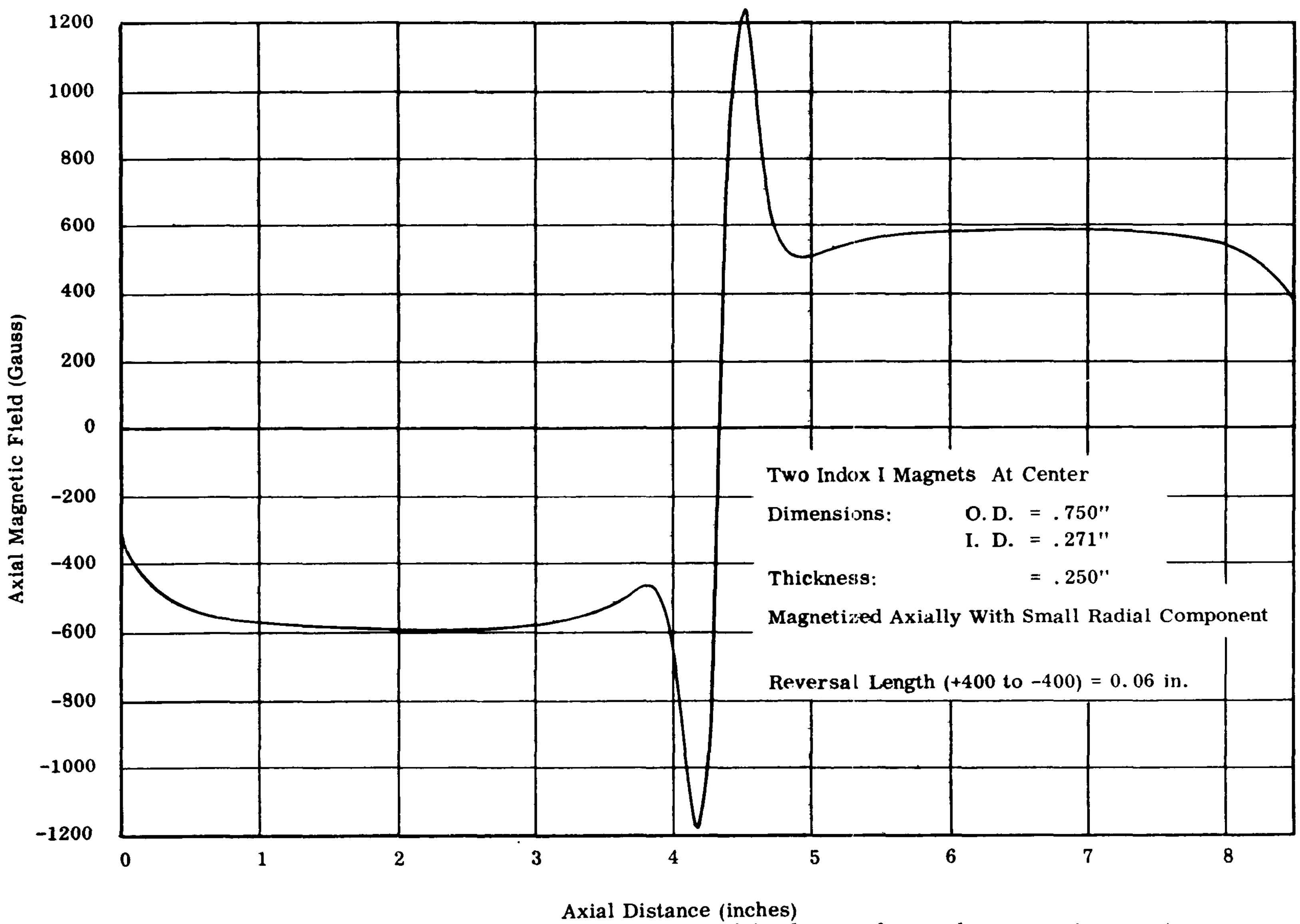

Fig. 5 - The reversal distance in this plot is reduced to 0.06 inch by the use of two Indox I ceramic magnets at the reversal plane. Their magnetization is predominately axial, with a small radial component.

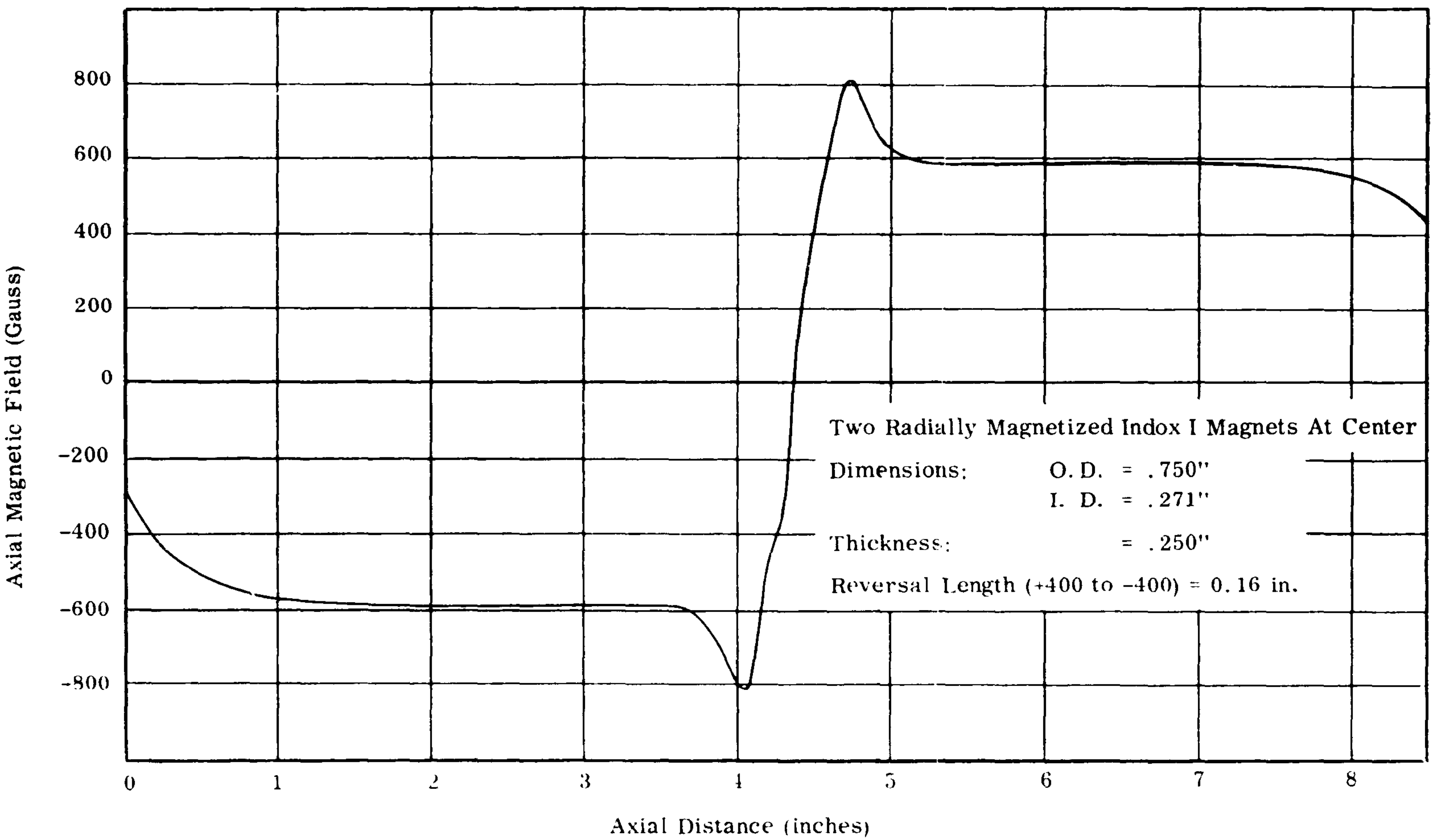

Fig. 6 - This field plot illustrates the effect of two Indox I magnets, with racial magnetization, in steepening the reversal. The reversal distance is 0.16 inch.

For this case the reversal distance is reduced to 0.58 inch. In Fig. 5 the pole piece is replaced with two small Indox I ceramic magnets at the center plane. These magnets are 0.25 inch thick, with an OD of 0.75 inch and an ID of 0.27 inch. They are magnetized principally in the axial direction, with a small radial component, and oriented with like poles together so as to aid the large magnets. The principal feature of magnetizing the small magnets in this way is that it suppresses the reverse component of field which always accompanies axial magnetization and which, if present, would cause a large dip in the field between the uniform portion and the high peak immediately preceeding the reversal. Here the reversal distance has been reduced to 0.06 inch. In Fig. 6, the Indox I magnets are radially magnetized. The value of the peak has been reduced, and the reversal distance increased to 0.16 inch.

Beam focusing tests were conducted using the assembly represented by the plot of Fig. 5. Ninety nine percent beam transmission was obtained with a helix voltage of 240 volts. At the design value of 180 volts, 95 percent transmission was obtained. Successive maxima and minima of transmission were observed with variation of helix voltage.

Ferrite Magnets

An additional reversed-field test was made using two opposed stacks of identical ferrite magnets. The individual magnets were ferrite discs 1.4 inches in diameter with a center hole 0.75 inches in diameter, and (.5 inches thick. The magnets were separated by Hipernik discs 0.014 inch thick, with a 0.25-inch center hole. These discs served as field straighteners, the disc at the center of the stack also acting as a reversal-plane pole piece. The field developed by this stack reached a maximum of 900 gauss near the ends, falling to 750 gauss in the middle of the straight-field sections. Focusing performance of this configuration was not as good as with the Alnico magnets. Beam transmission at rated helix voltage of 180 volts was only 75 percent.

Focusing adjustments with both the Alnico and ferrite reversed magnets were quite critical. The magnetic axes of the two magnets must be not only parallel but also colinear to achieve good focusing. In addition, the requirement of a steep reversal dictates the use of either suitably oriented boosting magnets at the center plane, or an inter-magnet pole piece with as small a diameter as possible. Either alternative adds to the complexity of the coupler. As shown in the tests, the lower the helix voltage, the more critical the adjustment and the more difficult the focusing problem.

This occurs because the scalloping period of the beam, in this case identical to the cyclotron wavelength, increases with helix voltage, as shown in the curves of Fig. 7. When the scalloping wavelength is long compared with the reversal distance, focusing through the reversal is relatively easy to obtain, particularly if field perturbers are used on either side of the reversal. Low noise considerations make it desirable to maintain the helix voltage at a low value. For this reason it appeared that the relative complexity of the reversed field structure and its critical adjustment characteristics tended to offset the advantages of light weight and ease of shielding.

2. Combined PM-PPM Focusing

Straight-field focusing and PPM focusing each have distinct advantages. Simplicity of the magnet and suitability for low-noise operation are characteristic of the straight-field. Light weight and ease of shielding typify the PPM method. Conceptually the advantages of each can be realized by combining the two methods, that is, by providing a straight-field over the gun region and the initial part of the helix, then making a transition into a periodic stack.

Previous focusing experience had shown that a uniform axial field of between 500 and 600 gauss was required to obtain noise figure in the 3 to 4 db range. The peak periodic field necessary to focus the beam should then be

$$\hat{B}_z = \sqrt{2}\, B_o$$

Where $\hat{B}_z$ = peak axial PPM field

B_o = uniform axial field

This problem has been previously studied by Chang[1], who gives two solutions for the transition region from uniform to PPM.

Magnetic Configuration and Field Measurements

Several configurations were tried to produce the desired theoretical field plot. In the first attempt, an end pole piece with an unshielded PPM stack was placed on the end of the large straight-field magnet. The results were poor for two reasons. First, the axial field along the centerline inside the straight-field magnet drops from 600 gauss midway between pole pieces to about 300 gauss near the pole pieces. This drooping characteristic is typical of long straight-field magnets.

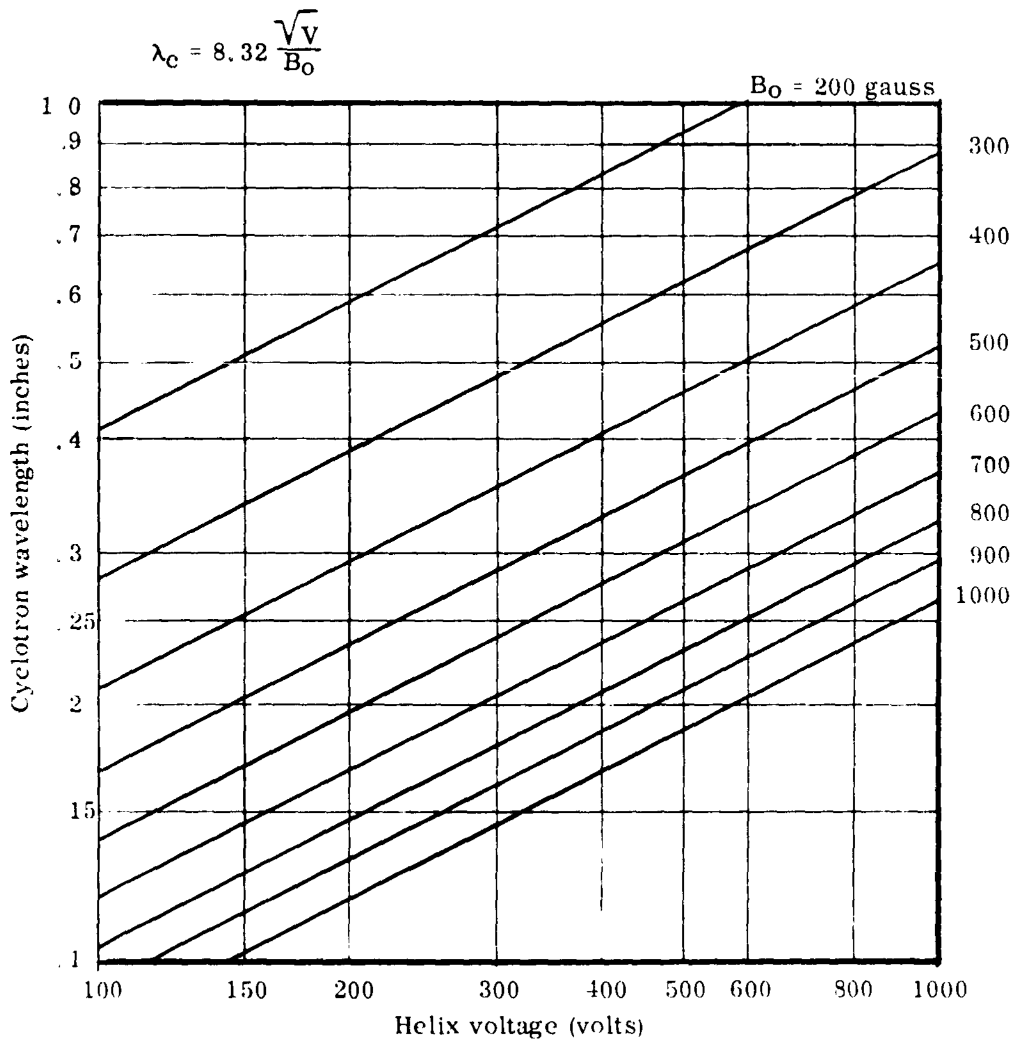

Fig. 7 - Cyclotron wavelength vs beam voltage, with magnetic field as a parameter. For low space charge, the cyclotron wavelength is the same as the scalloping wavelength of the beam.

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The second reason is that very strong fringing axial magnetic fields exist outside of the end pole piece. When an unshielded PPM stack is placed on the end pole piece, the resulting field plot is a periodic field superimposed on top of the strong fringing field.

This result suggested a fairly obvious remedy. The drooping field inside the straight-field magnet could be corrected by using a flux concentrator in the form of a reentrant steel sleeve. Inside the sleeve the field is maintained at essentially zero gauss, rapidly rising to the full value of the axial field just beyond the end of the sleeve. In addition, by extending the sleeve in the opposite direction, beyond the end of the magnet, the strong external fringing field on the axis would be eliminated. The periodic stack could be placed inside the shield.

An assembly of this description was made up and tested. The results of the test showed that both the droop in the internal straight-field and also the bias of the PPM stack were eliminated. Subsequently an additional structure, designed to provide for focusing tests, was built. Details of this assembly are shown in the sketch of Fig. 8. The axial field is shown in Fig. 9.

Focusing Tests

Focusing was found to be heavily dependent on helix voltage, as would be expected. With 194 volts on the helix, 100 percent beam transmission with a beam current of 125 μa was obtained, with the tube extended one inch into the periodic stack. Focus was lost when the tube was pushed further than one inch into the stack, due most likely to variations in the peak field values of individual magnets. Variation of the first three anode voltages could also cause defocusing. With the helix voltage increased to 250 volts, with a 125-μa beam, anode voltage variation did not produce defocusing. Full transmission was obtained through 1 1/2 inches of PPM stack (15 magnets) with 355 volts on the helix.

The period of the stack was .210 inch. Note from Fig. 7 that with a magnetic field of 500 gauss (value in the uniform region) and a voltage of 200 volts on the helix, the cyclotron wavelength is .230 inch. In other words, the focusing was marginally stable with the scalloping (cyclotron) wavelength slightly longer than the stack period. The scalloping wavelength increases as the square root of helix voltage. With 355 volts on the helix, giving a scalloping wavelength approximately 1.5 times the period, focusing was stable.

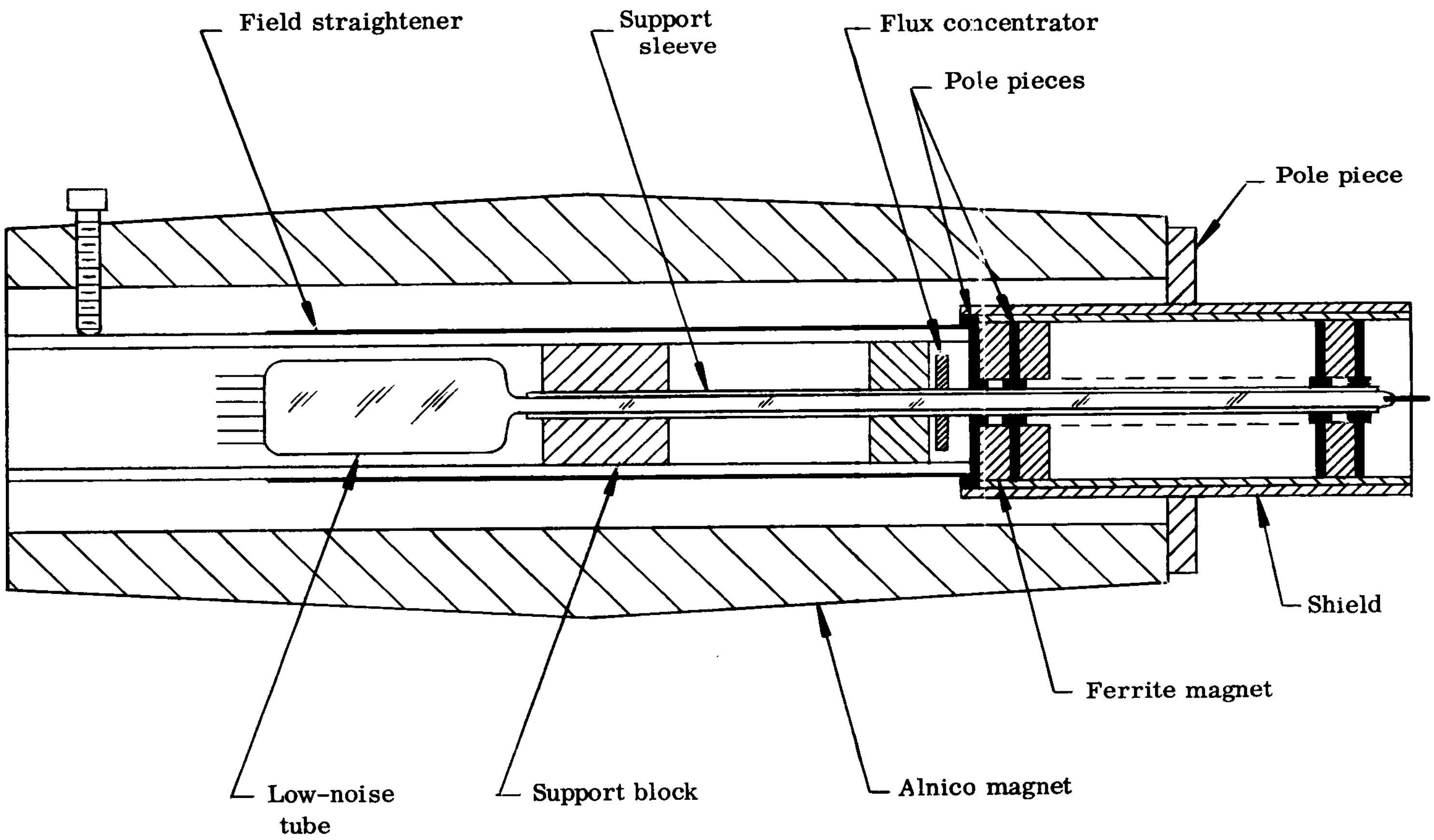

Fig. 8 - Cross-sectional sketch of experimental PM-PPM focusing assembly.

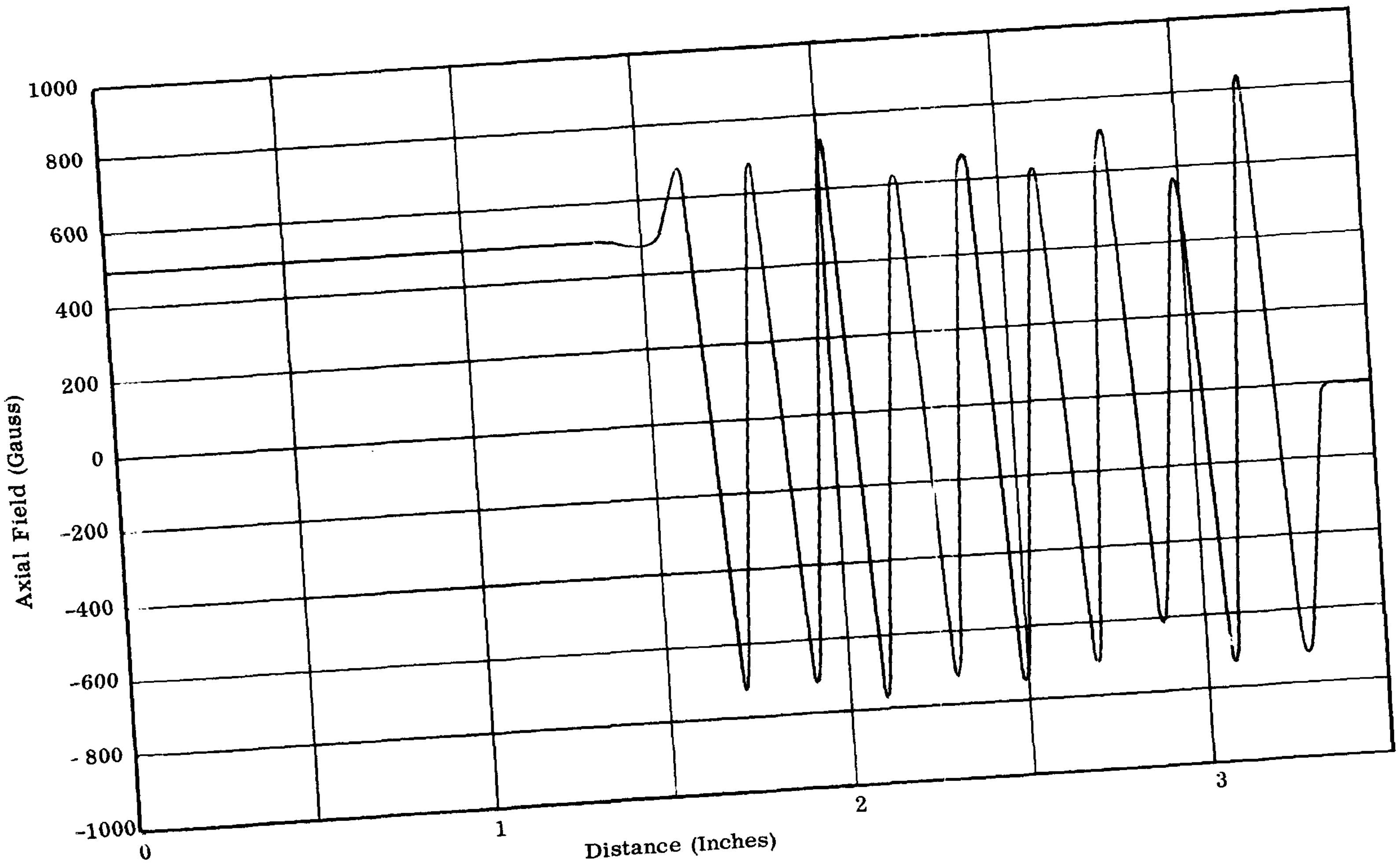

Fig. 9 - Axial field plot of the PM-PPM assembly.

From these results it became clear that to properly utilize PM-PPM focusing the helix voltage would have to be increased, or the period of the stack reduced. Further reduction of the stack period would be impractical as well as costly. Raising the helix voltage would necessitate a major redesign of the tube, and so was ruled out as a solution. In this light the advantages of straight-field focusing became clearer, as discussed in the next section.

3. Straight-Field Focusing

Certain disadvantages inherent in both reversed-field and PM-PPM focusing led to a consideration of the possibilities of uniform straight-field focusing. The results sought were.

1) A simple, readily reproducible magnetic circuit.

2) A focusing system which would not be influenced by external fields or adjacent magnetic material, and which would permit operation of identical units side by side.

3) A package of minimum size and weight, consistent with these requirements.

For a straight-field magnet, Alnico 5 is the clear choice, provided the axial field does not have to exceed 600 gauss. The principal problem to be overcome was that of shielding. A straight-field magnet has a strong external fringing field. This field falls off approximately exponentially in the near zone, and as the cube of distance in the far zone (distances large compared with magnet dimensions). The addition of shielding around the magnet increases the external permeance, or equivalently, decreases the reluctance. The result is that the net flux generated by the magnet increases, but principally in the external path. The mmf of the magnet and the axial flux are decreased.

Shielding

Figure 10 is a sketch showing an effective means of shielding an Alnico 5 magnet. The outer steel cylinder serves as the main structural element in addition to its shielding function. The inner, shorter, cylinder reduces the peak of the external fringing field by providing an additional flux shunt where it is most needed.

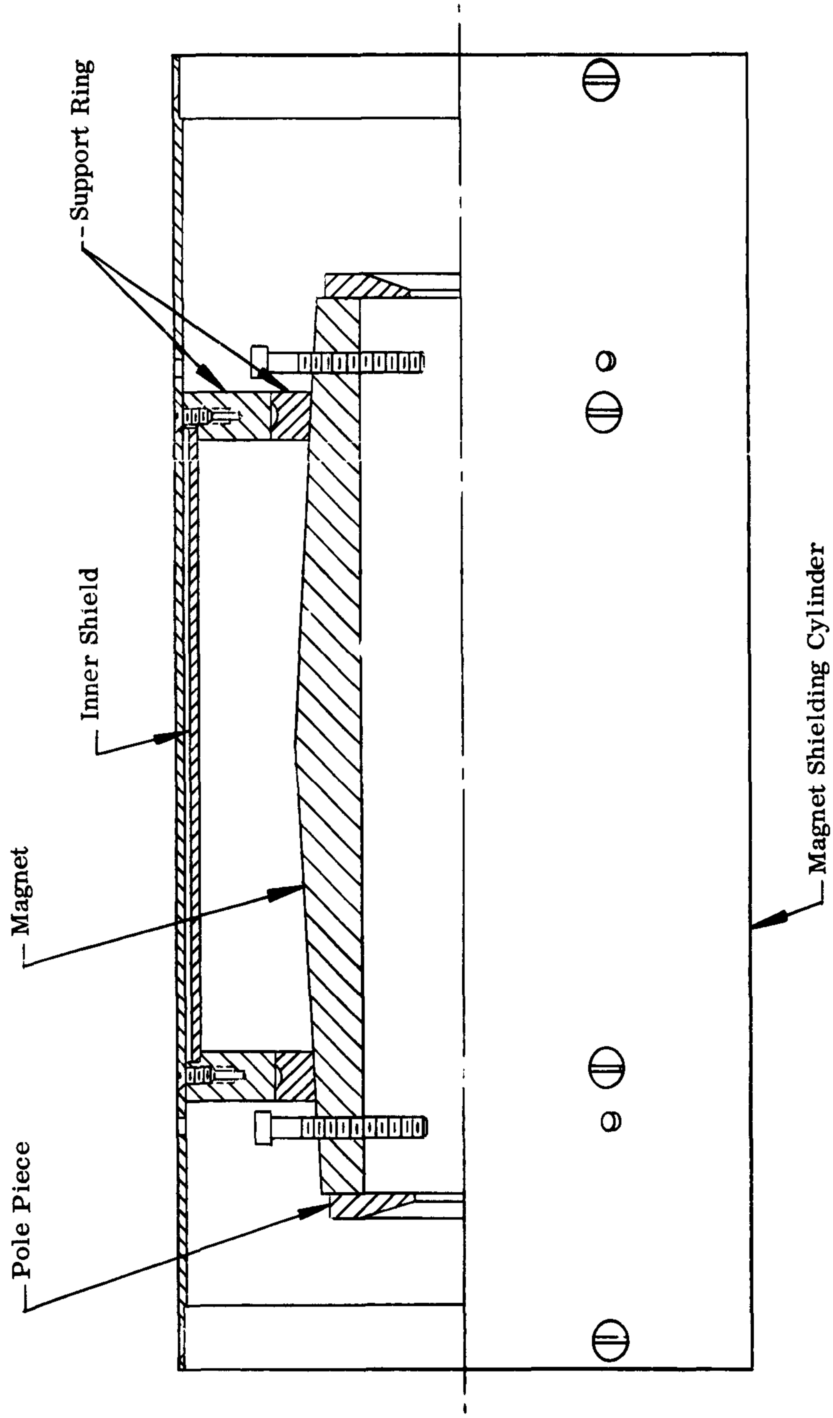

Fig. 10 - Sketch of a method for mounting and shielding a straight-field Alnico 5 magnet.

The solid curve of Fig. 11 is a plot of axial field of a seven-inch long magnet inside such a double-walled shield. The dashed curve shows longitudinal field measured on the outside wall of the 4.5-inch diameter outer shield. The dotted curve shows longitudinal field at the same diameter in the absence of shielding. Two features are significant. First, the residual external field is sufficently low that multiple units of the same type can be operated in close proximity without interference. Secondly, the field on the axis is reduced by this shielding by approximately 150 gauss. For best noise performance it is necessary to have a field of about 750 to 800 gauss at the cathode of the tube.

Field Peaking and Straightening

Peaking the field at the cathode has two effects. First, it yields a more stiffly focused beam in the gun region, rendering it less susceptible to the effects of electrostatic lenses formed by the anodes. Secondly, it causes the beam to expand as it flows into the region of lower flux density. This results in a larger beam-to-helix diameter ratio and tighter coupling, hence an increase in gain. The increased gain, or more specifically, the increased gain per unit length, reduces the effect of helix attenuation on noise figure[2,3]. The mechanism used to achieve this peaking is shown in the photograph of Fig. 12. The pole piece and steel sleeve at the right end of the cylinder in the foreground form a reentrant structure which boosts the field in the region of the cathode to 750 gauss or higher.

To prevent defocusing by transverse magnetic field components, it is necessary that the field have a high degree of straightness on the axis. The straightening should be done without any significant effect on the axial component of field. The basic idea of the straightener is to provide a low reluctance flux path across each transverse plane of the magnet. This operation is illustrated in the sketch of Fig. 13, showing the operation of a flux shunt in reducing the transverse field on the axis. Two basic types of field straighteners have been used. The first consists of thin rings of high permeability material separated by non-magnetic spacers. The second uses iron wire wound on a cylinder in the form of a helix. The latter form was adopted here because of its greater simplicity and ease of fabrication. The straightener assembly is shown in the photograph of Fig. 12, where the wire is seen wound on the stainless steel tube. Figure 14 is a cross section of the straightener. Best results were obtained by using two layers of 0.028 diameter iron wire, separated by copper foil. Results obtained with this type of straightener are typified in Fig. 15, showing that axial transverse components of less than one gauss are readily obtainable.

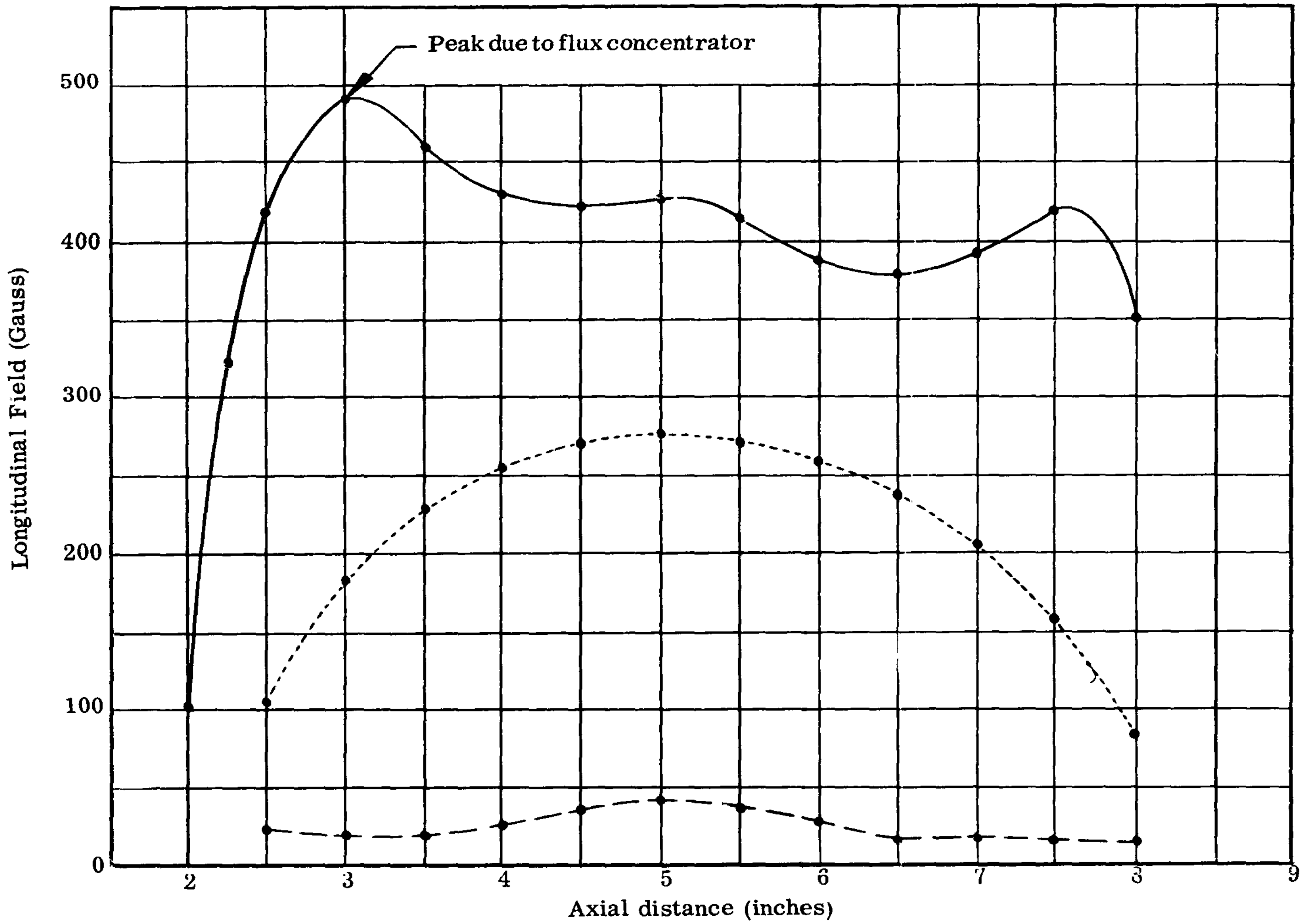

Fig. 11 - Field plots for a seven-inch Alnico 5 magnet within a double-walled steel shield 4.5 inches in diameter. The solid curve is field along the axis of the magnet. The dashed curve shows the axial component of external fringing field along the exterior of the shield, and the dotted curve indicates the same field in the absence of the shield.

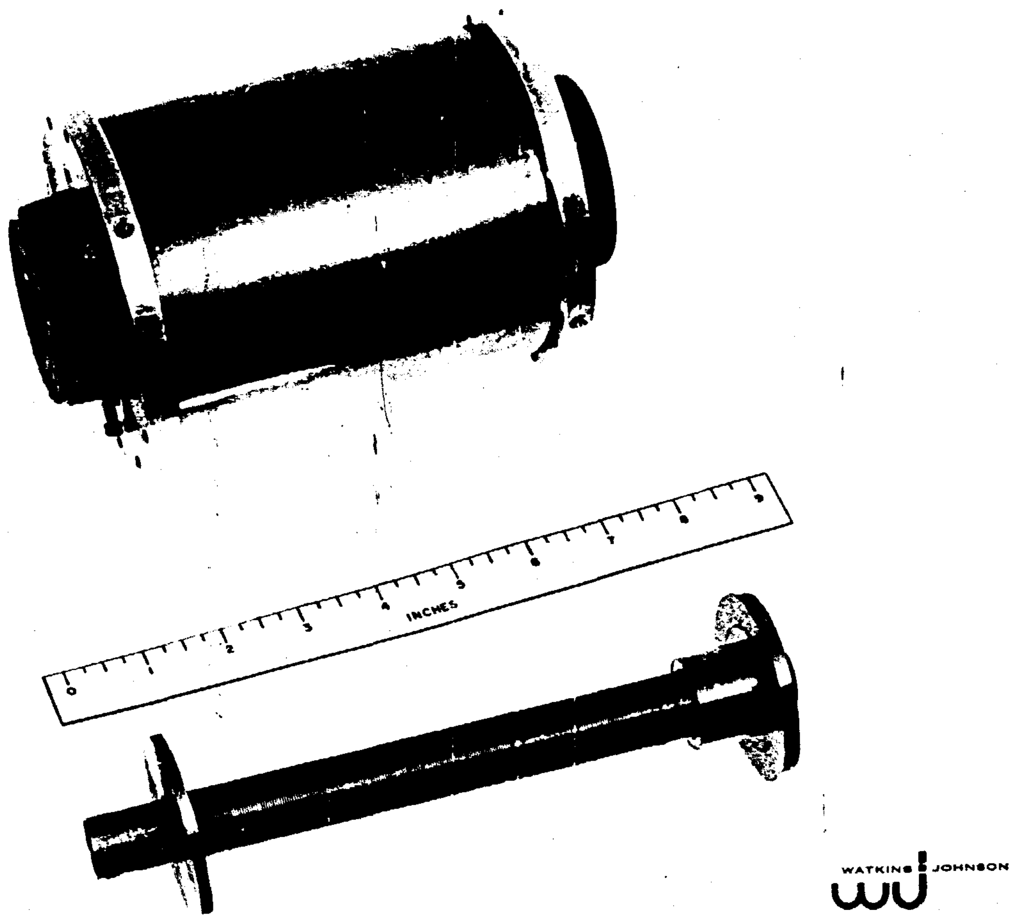

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Fig. 12 - Photograph of magnet with inner shield can, and field peaker and straightener assembly. The pole piece and flux concentrator at the right end raises the field at the cathode to approximately 750 gauss.

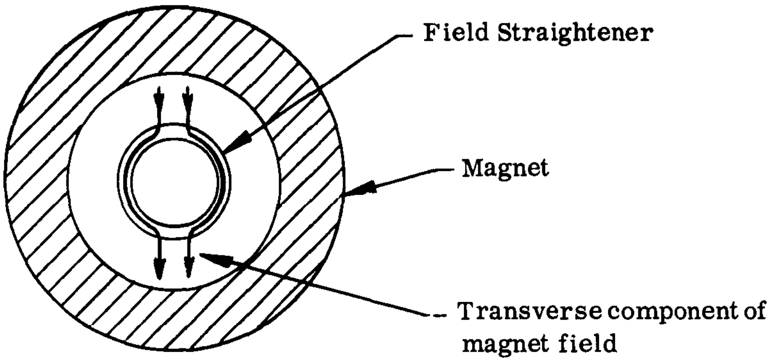

Fig. 13 - Sketch showing operation of the field straightener as a flux shunt in reducing the value of transverse field on the axis of a straight-field magnet.

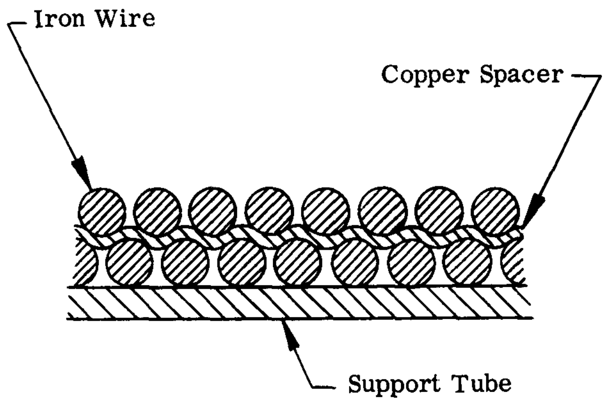

Fig. 14 - Cross sectional sketch of the field straightener windings.

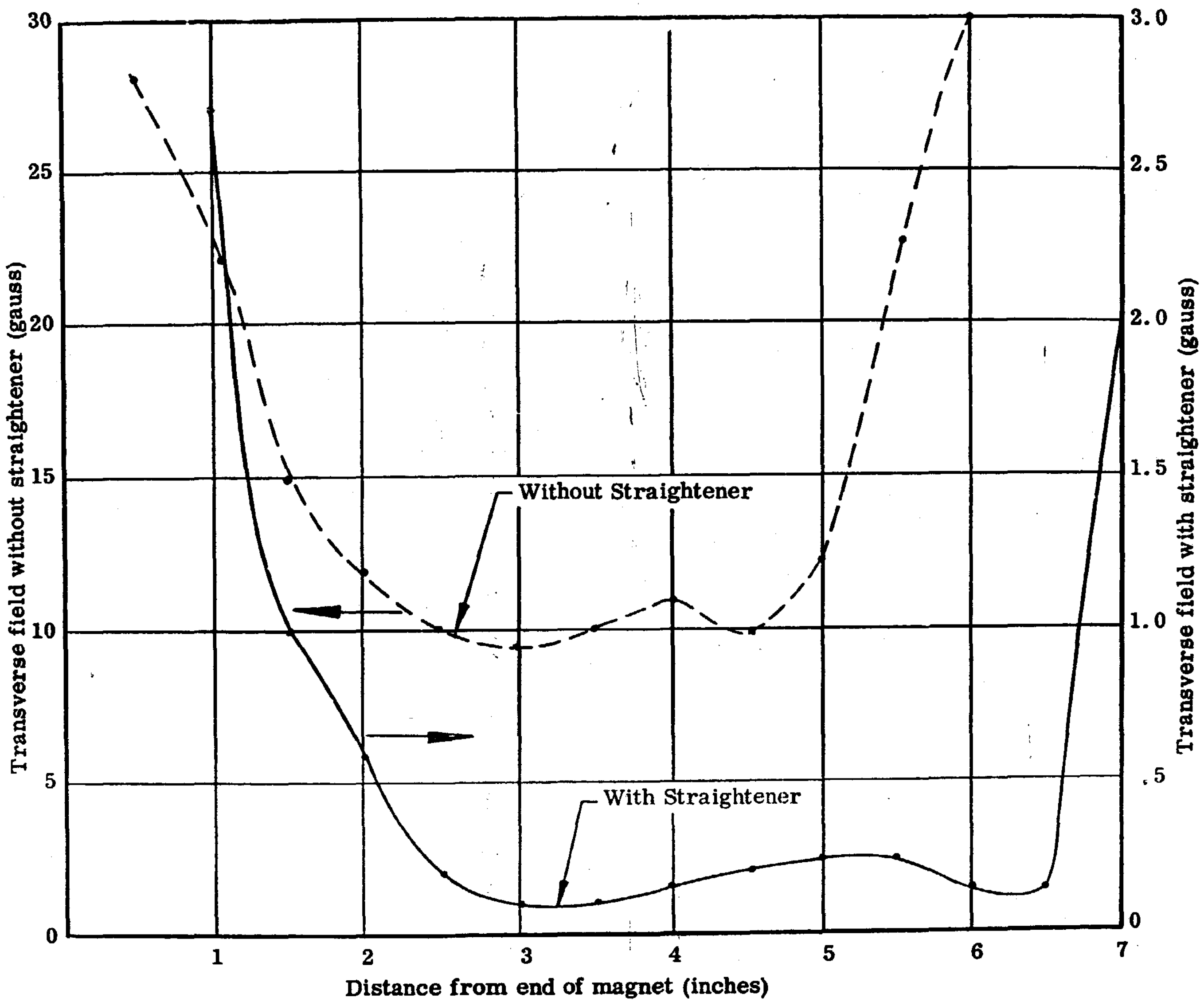

Fig. 15 - These curves show the effect of the field straightener on transverse magnetic field. Note that a reduction of as much as a factor of 100 is obtained in using the straightener.

Magnet Design

To specify the magnet for a given straight-field application, it is necessary to know the magnet I. D. and its length. With these two parameters, the other dimensions can be specified, following a procedure given by Glass[4]. To further facilitate the work, additional sets of curves, based on Glass' work, have been prepared. These curves are shown in Figs. 16 and 17. They show, respectively, normalized O. D. vs normalized I. D. and magnet weight (divided by the cube of length) vs normalized I. D. In each case the normalization is with respect to magnet length. It is desirable to keep both the length and I. D. as small as possible. The length and weight of the magnet are both highly dependent on the I. D. This is illustrated in the sketch of Fig. 18, which is a plot of weight of a straight-field magnet suitable for focusing a beam 5 inches long. These curves are based on the assumption that the magnet length should be equal to the beam length plus twice the inside diameter, which tends to be slightly pessimistic.

The advantage of reducing magnet length is even more striking when the effects of shielding the external field are examined. The leakage flux around a straight-field magnet increases very rapidly with magnet length, as described by Glass[5]. Accordingly, the difficulty of shielding increases rapidly with increasing length. For example, increasing the magnet length from 7 to 7.5 inches approximately doubles the external field at the surface of the shield. Developments in both tube and coupler which made possible the necessary reductions in magnet length and diameter are described in Section B.

A design for a magnet with 1.25-inch I. D. and 7-inch length was worked out. Four magnets of this type, designated R-11, were obtained from General Magnetic Corporation. Provision was made for subsequent cutting and grinding of the ends to further reduce the length if the magnet performance would allow. The intent was to use the magnets in a shield with four-inch O. D. in which case minimum length would be required. Typical field measurements on the R-11 magnets are shown in Fig. 19. This plot is for the magnet only, with no shielding or straightening.

The final package configuration of the magnet assembly is shown in Fig. 20. The magnet was cut to a length of 6.5 inches. Also, the wall of the peaker had to be reduced from 3/16 to 1/8 inch in order to allow sufficient clearance with the magnet I. D. Figure 21 is a plot showing typical axial and transverse fields of the assembly of Fig. 20.

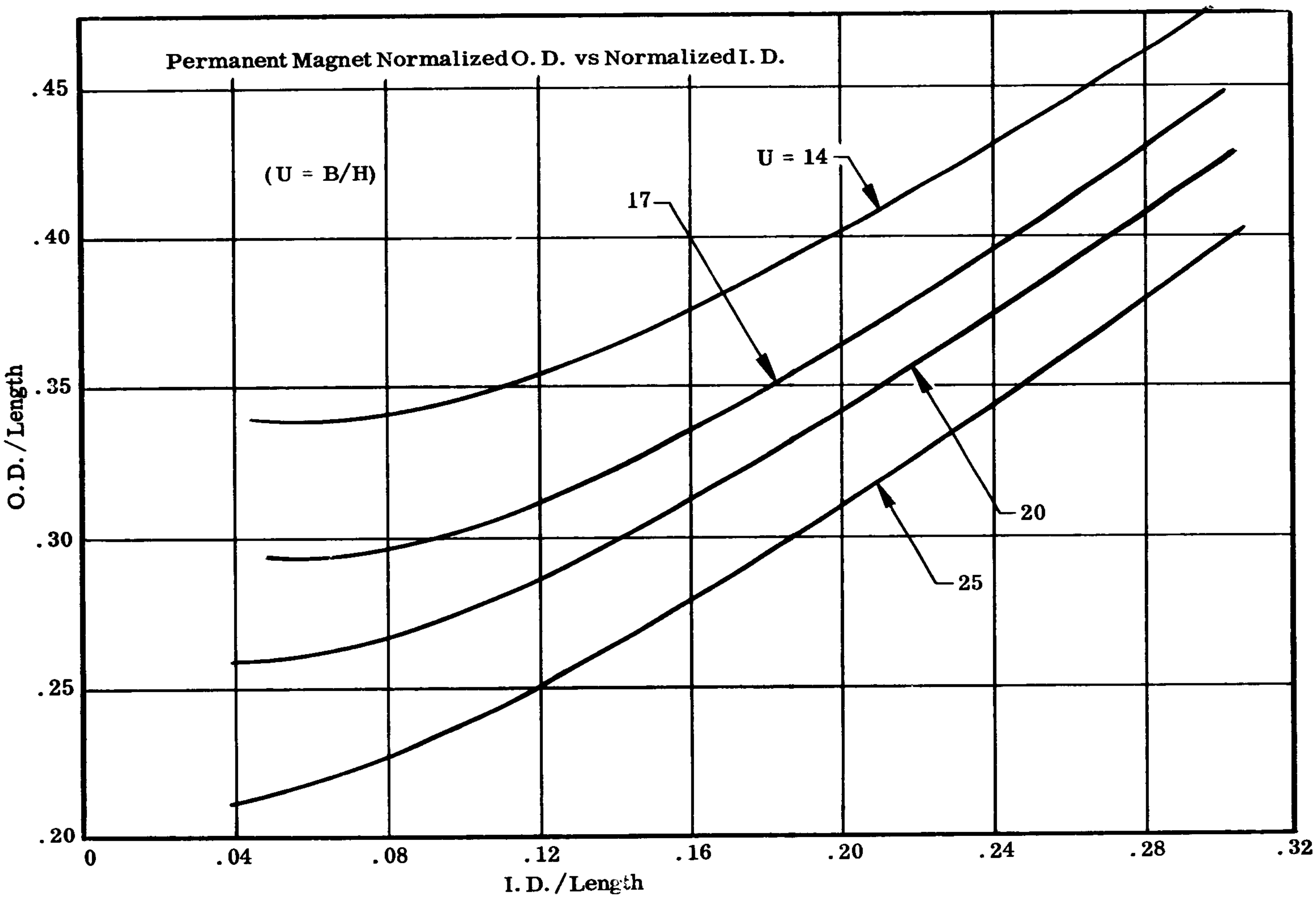

Fig. 16 - Curves showing the ratio of outside diameter-to-length for a straight-field magnet as a function of inside diameter-to-length ratio. The parameter U is the ratio of B/H, the permeance coefficient for the magnet.

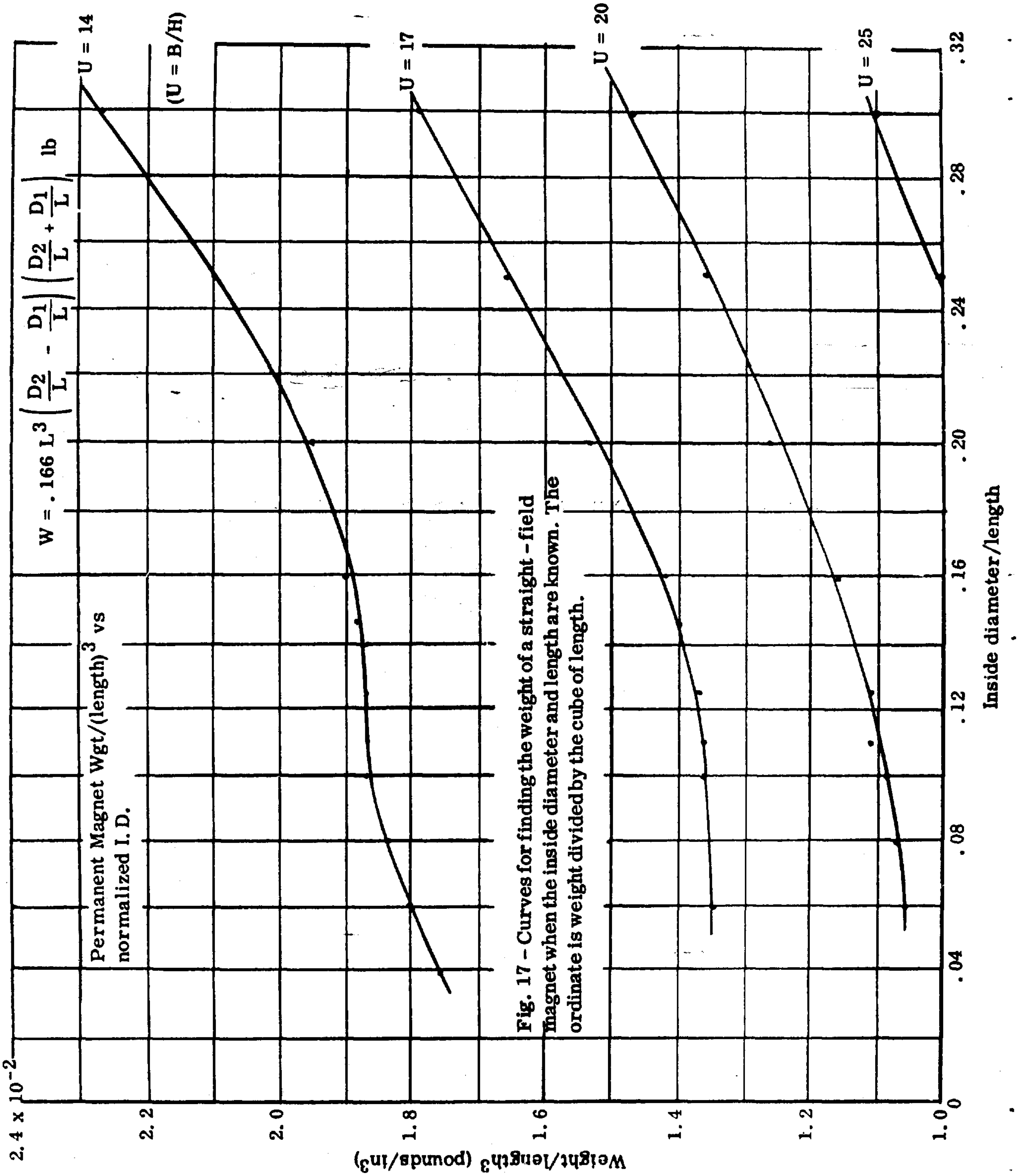

Fig. 17 - Curves for finding the weight of a straight-field magnet when the inside diameter and length are known. The ordinate is weight divided by the cube of length.

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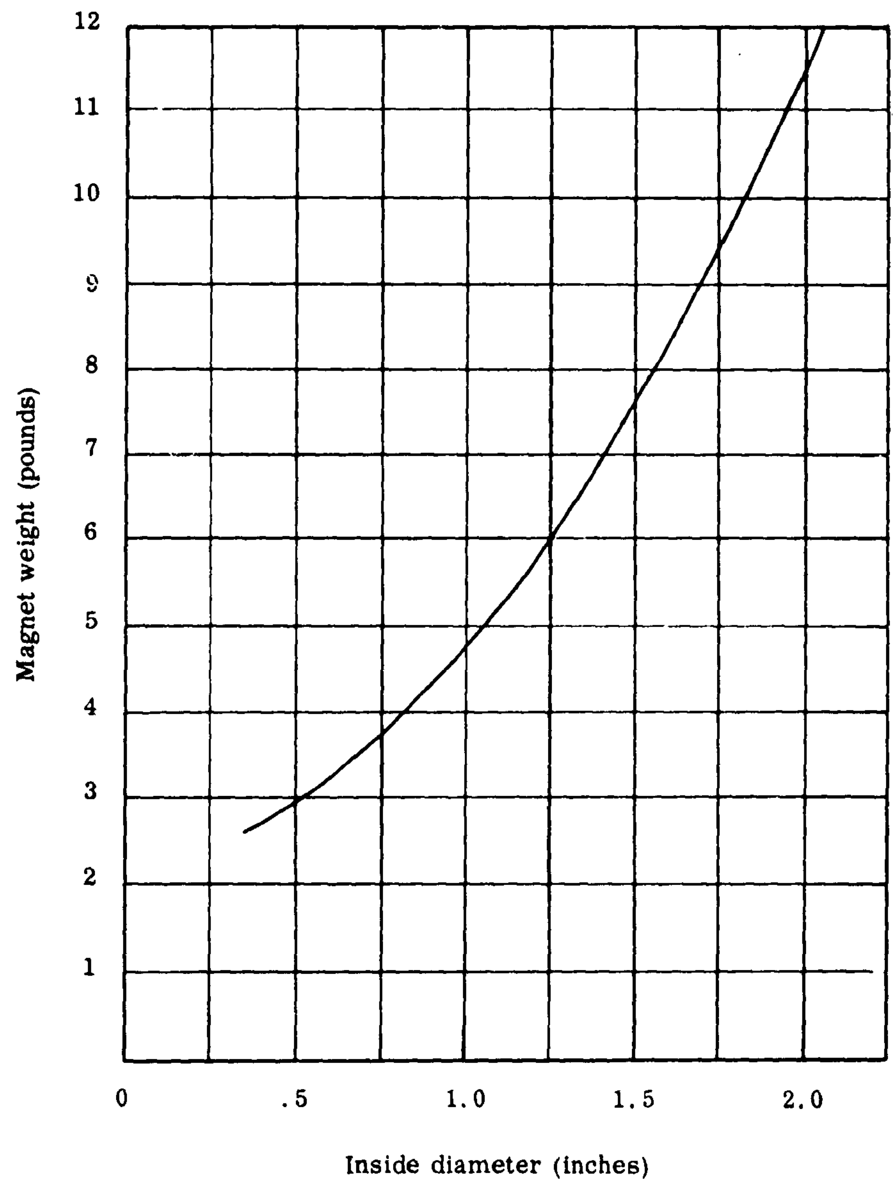

Fig. 18 - Magnet weight vs inside diameter, for focusing a five inch long beam.

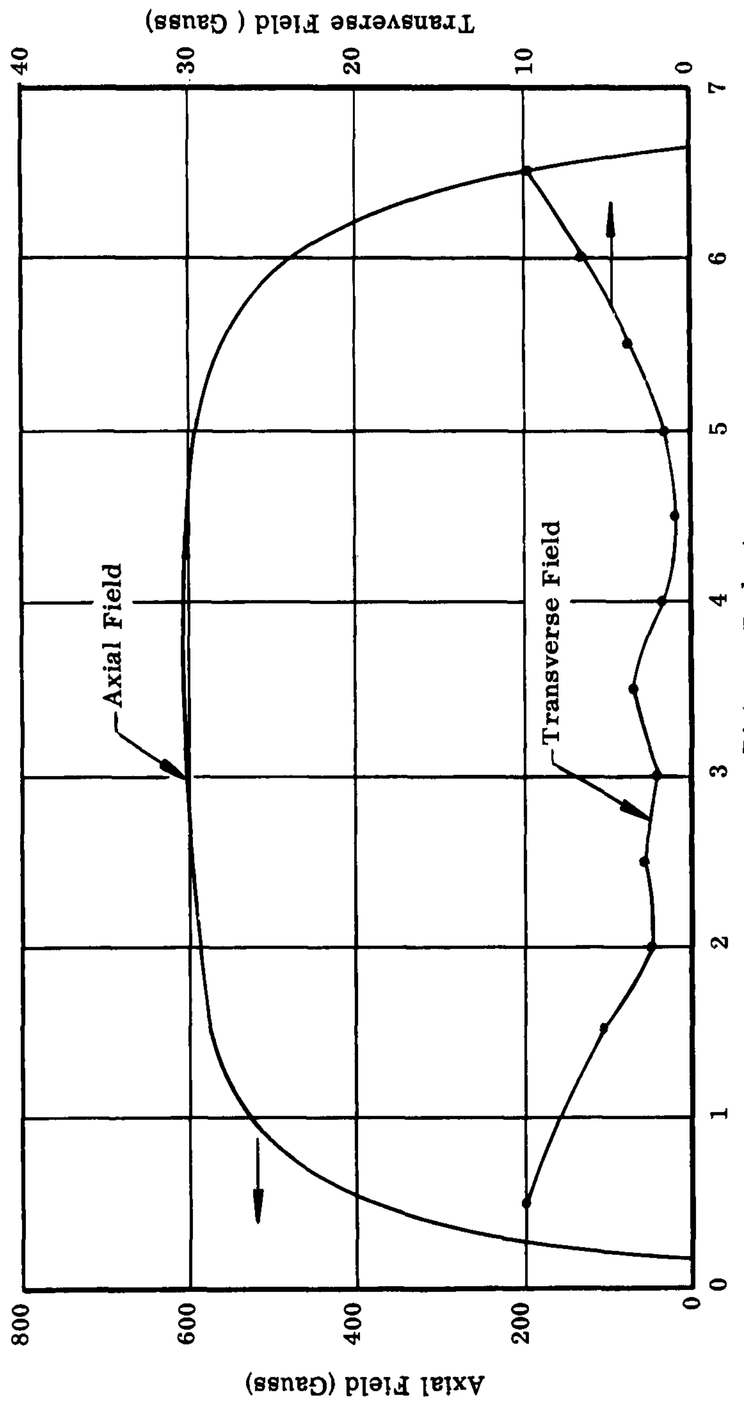

Fig. 19 - Plots of axial and transverse field for a type R-11 magnet.

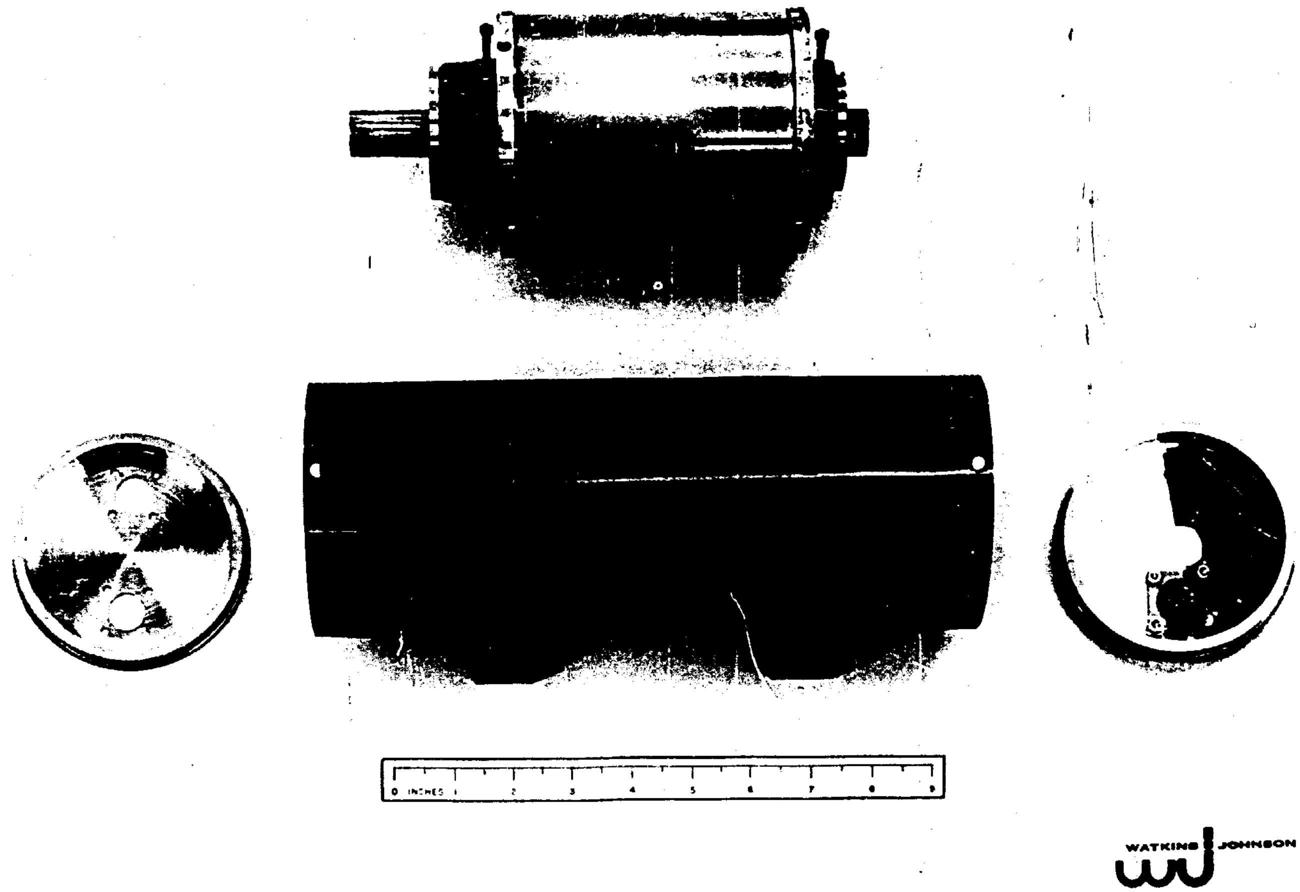

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Fig. 20 - Photograph showing details of the straight-field magnet package. The voltage divider for supplying tube operating potentials is seen on the right end cap.

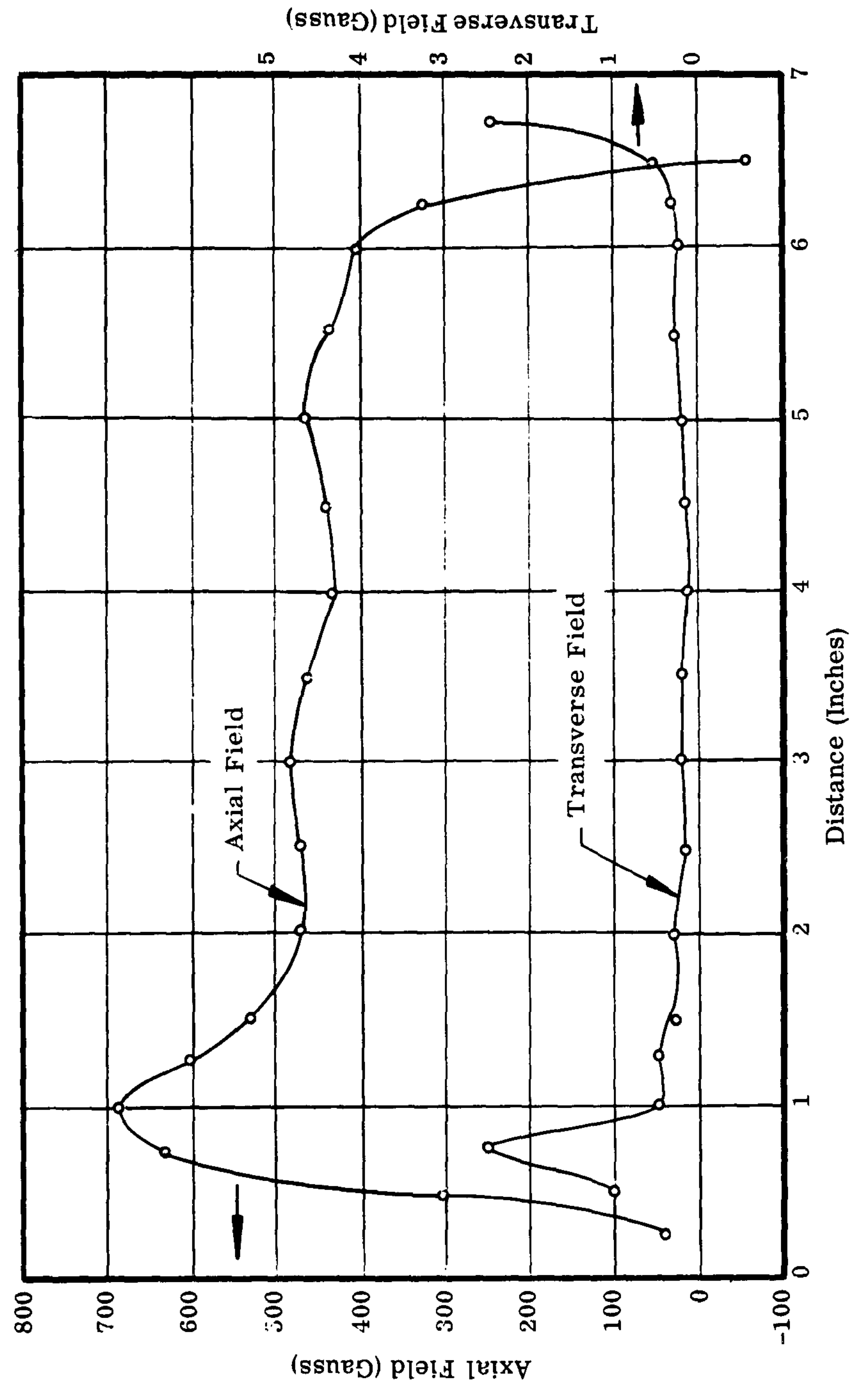


Fig. 21 - Plots of axial and transverse field of the completed magnet assembly of Fig. 20.

A prime advantage of this type of magnet assembly is that it can be made up as a unit, with shielding, straightening, and peaking included. Alignment adjustments are reduced to a minimum. The tube and coupler are assembled as a separate independent unit and then installed into the focusing package. After installation of the tube-coupler assembly, the shielding circuit and mechanical packaging are completed simultaneously by attachment of the steel end caps.

B. Tube And Coupler Development

1. Tube

Short beam length is a key feature of the tube . This minimizes the length of the magnetic field. In addition, the low helix voltage contributes to high specific gain and reduces the contribution of helix attenuation to noise figure. Uniformity of the helix is also an essential factor in the achievement of high specific gain. The developments discussed below are those which contributed to the realization of these objectives.

Pin-Seal Input Match

The conventional method of introducing signal onto the helix is by means of a short antenna attached to the front end of the helix. This antenna is placed across an E-field gap in the input cavity transducer, as shown in the sketch of Fig. 22. The antenna, isolation helix, and input snout sleeve,combined, occupy approximately an inch and a quarter of axial length. An input configuration which eliminates the antenna and isolation helix was developed in this program. It consists simply of a direct connection to the helix by which both the rf signal and dc operating potential are introduced. This input match is illustrated in the sketch of Fig. 23. The input coaxial line is connected directly to the tungsten pin which in turn is connected to the helix snout by a thin platinum tab. At the front end of the gun stack is a ceramic alignment anode which locates on the helix snout. This provides front end support of the gun and secures accurate alignment of the gun to the helix. The alignment anode is made of ceramic to prevent disturbance of the match which results from a metallic anode.

The advantages of this match are several. It shortens the beam length by more than an inch. It is simpler to build and to adjust than the cavity-antenna match. It greatly simplifies the external coupler, since the cavity with its numerous parts and critical tolerances is eliminated. Finally, it has excellent matching properties. A VSWR of well under 2:1 can be obtained over a full octave. Across the 2.7-3.3 Gc band, an input VSWR of 1.3:1 is feasible.

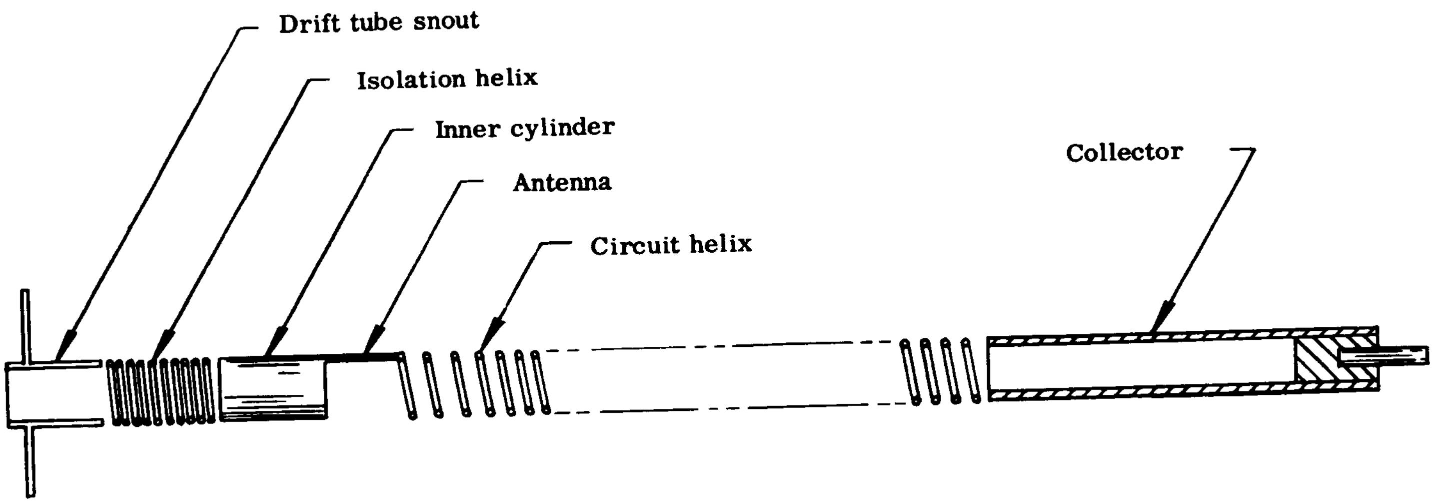


Fig. 22 - Sketch showing conventional helix assembly with matching elements for cavity transducer input.

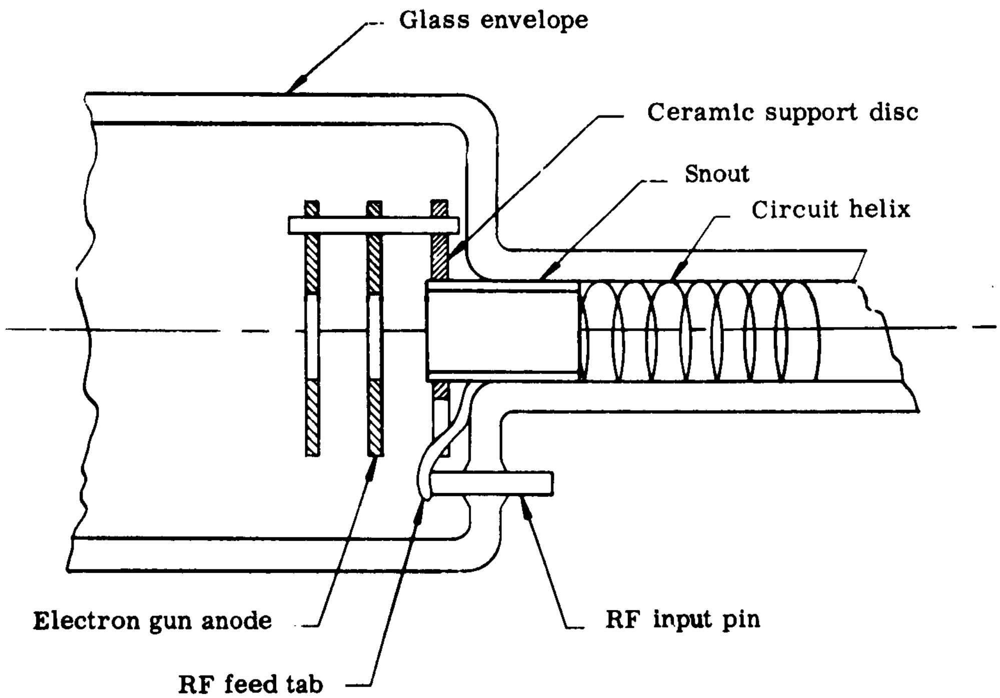


Fig. 23 - Sketch showing details of the pin-seal rf input match. The front end of the gun is supported by the ceramic alignment anode, which is notched to provide clearance for the input pin.

Ruggedized Helix

For a high degree of pitch uniformity in the helix it is essential that each turn individually be locked in place. A method has been developed whereby this is done using the glass envelope. The method is termed "scrunching", for lack of a more descriptive term. It consists of pressing the glass helix barrel down onto the helix along three lines of contract over its entire length. This is done in a weighted jig at a temperature of 650°C. Uniformity of helices produced by this method is tested in a device which performs a scanning measurement of phase velocity over the full length of the helix. The results of this measurement, reproduced in Fig. 24, constitute a criterion for acceptance of the helix into a final tube assembly.

Electron Gun

The gun design was evolved by essentially empirical methods. It provides the required low-velocity drift region near the cathode, followed by a transducer section which transforms the beam impedance to the value appropriate for the helix potential. The beam is hollow, being drawn from a cathode with 0.040-inch O. D. and 0.033-inch I.D. Anode apertures in the gun stack are 0.094 inch in diameter, or 2.3 times the nominal beam O. D. A smaller aperture size results in increased lens effects, which can lead to an increase in noise figure in conjunction with the fixed field value of the permanent magnet. Several of the anodes are internally tied together, as depicted in Fig. 25. This calls for the application of five voltages with nominal values (in order of increasing distance from the cathode and taken with respect to cathode potential) of 6, 0, 25, 70, and 150 volts. These voltages are provided by a resistive divider network included as an integral part of the package, as described below in Section C.

Small-Diameter Envelope

To maintain the magnet diameter at a minimum it is necessary that the tube envelope and the coupler which provides its physical support also have as small diameters as possible. To this end, the gun bulb diameter was reduced from one inch to slightly over 1/2 inch. This was achieved by the development of a reduced-diameter pin base, carrying eleven pins, and by reducing the diameter of the gun stack from 0.82 inch to 0.38 inch. The results of this size reduction are made clear in the photograph of Fig. 26, comparing a WJ-253-5 with its predecessor, the WJ-211.

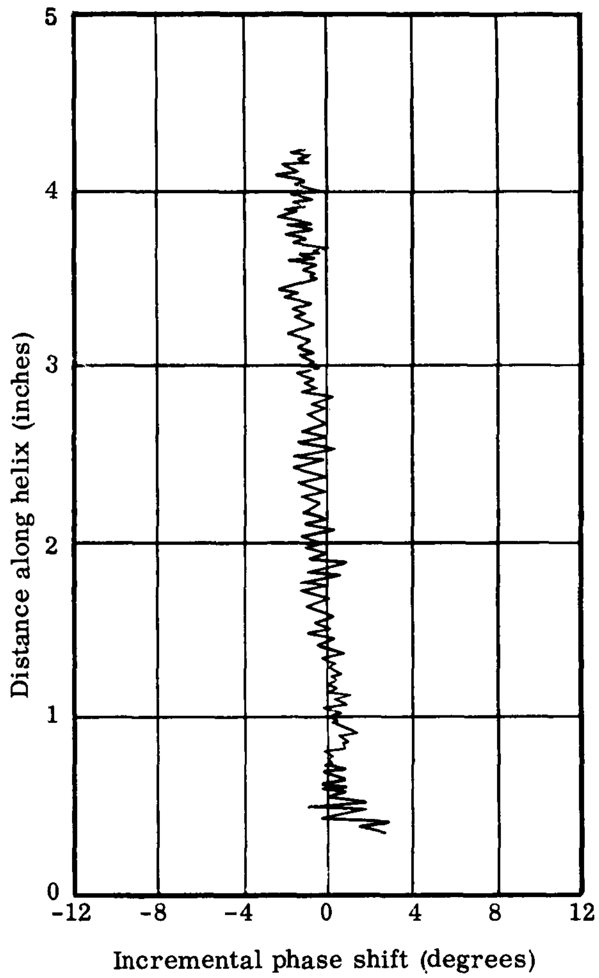


Fig. 24 - Incremental variation of phase velocity along the helix. The curve shows variation in phase length over a section in which the total phase length is about 1100 degrees.

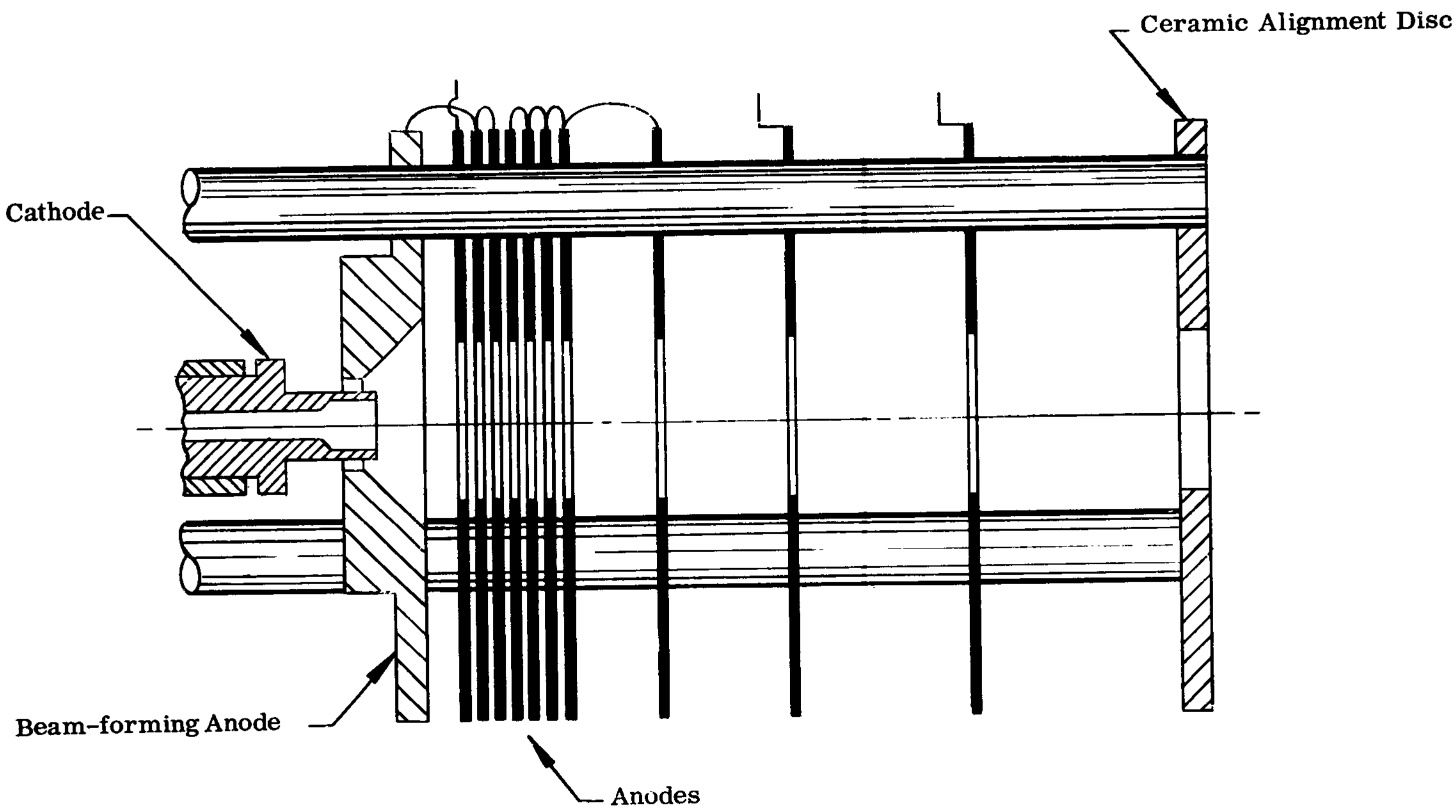


Fig. 25 - Sketch showing the gun stack of the WJ-253-5

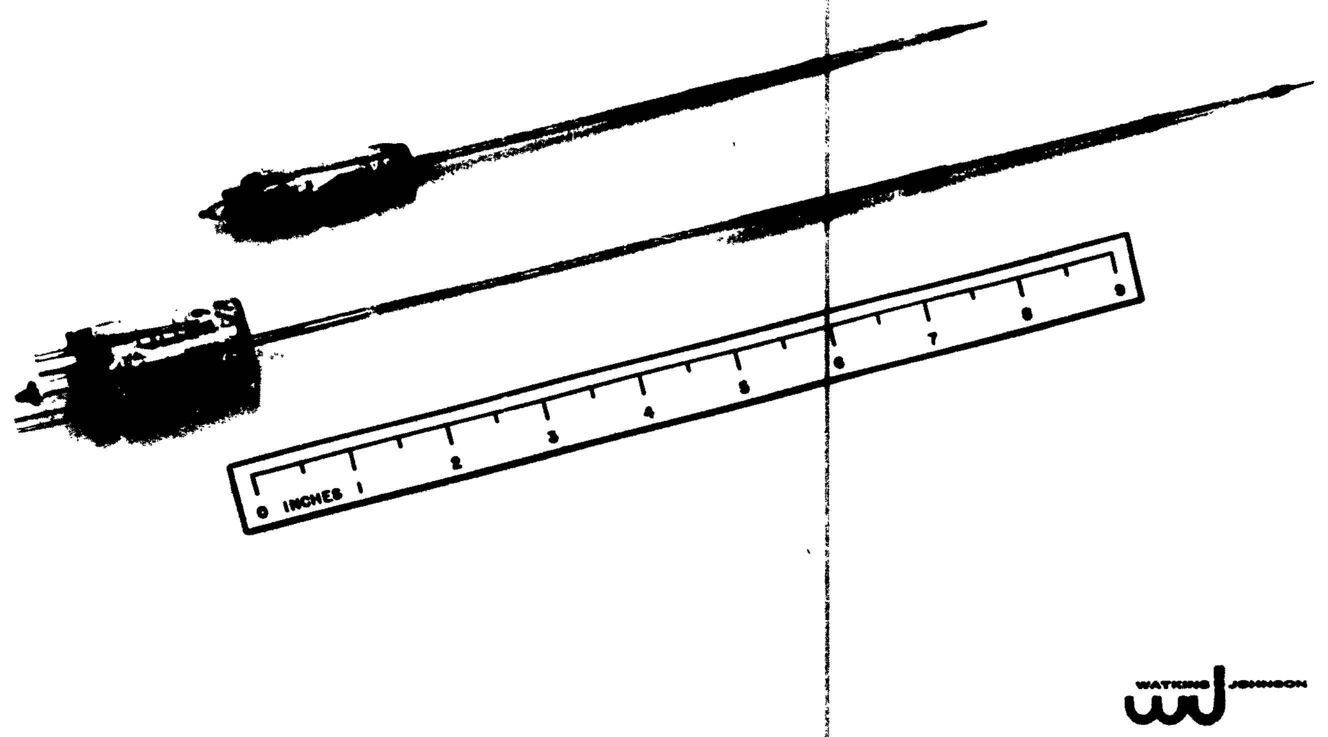


Fig. 26 - This photograph, showing a WJ-253-5 and a WJ-211, its solenoid-focused counterpart, illustrates the reduction achieved both in length and bulb diameter.

2. Coupler

Figure 27 is a photograph of the coupler designed to provide a pin-seal input match, output coupling helix, and to take advantage of the size reduction afforded by the small-diameter bulb described above. The construction is simple, consisting of a brass tube with milled-out half sections. This provides accessibility as well as ruggedness and easy assembly. The principal elements of the coupler are the input block, dispersive sleeve, output block with coupling helix, and collector block. The entire assembly slides into the 3/4-inch O. D. stainless steel tube held by the pole pieces of the magnet. The coupler is adjusted to the proper axial position (determined by the coincidence of the cathode with the peak of the magnetic field) and locked in place by a hose clamp which tightens on the stainless steel tubing. Including the support tubing, the over-all diameter of the coupler is 3/4 inch, as compared with 1 3/8 inch for the WJ-211 coupler.

C. Description Of End Product

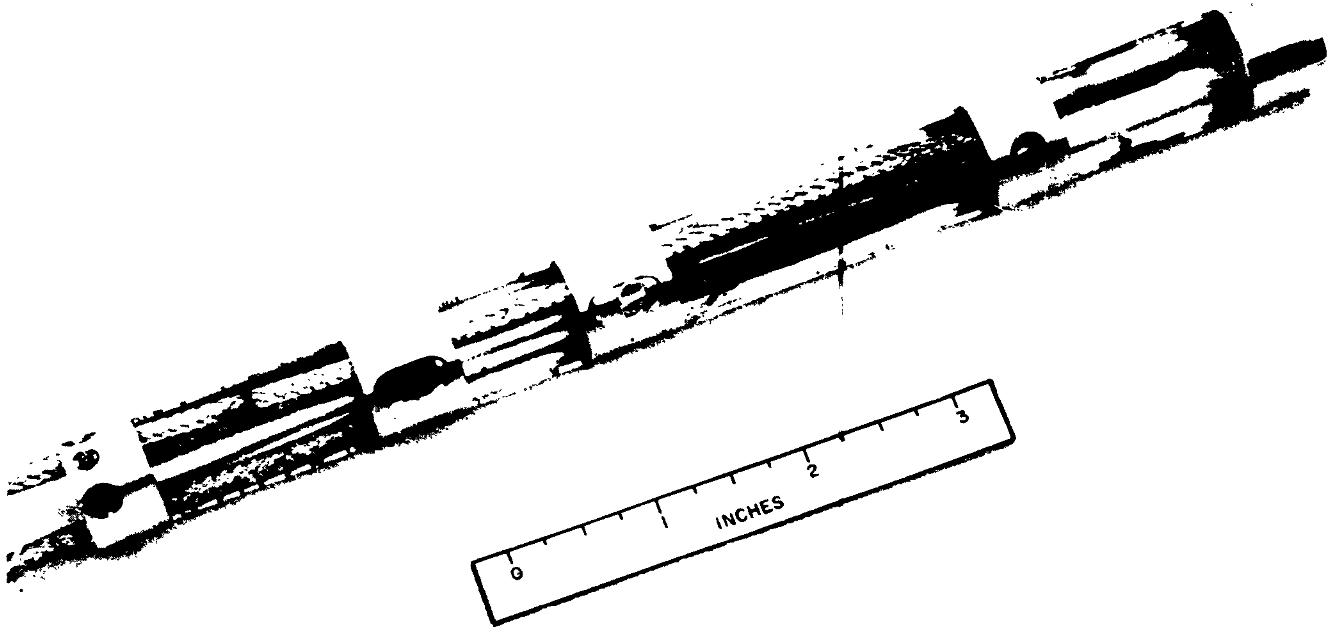
The finished amplifier package is shown in the photograph of Fig. 28. The outline dimensions are 4 inches diameter by 10.9 inches long, excluding connectors. operating voltages are applied at one end through an Amphenol type 67-02E12-7P receptacle. Type N jack rf fittings for input and output are located at the other end.

Operation of the amplifier is greatly simplified by the use of a resistive divider network mounted on the inner face of the dc end cap. This network, visible in the photograph of Fig. 20, is fed with a fixed external voltage of - 200 vdc, measured with respect to the case at ground potential. It provides all the operating voltages required by the anodes and the helix. Each of voltages can be varied by adjustment of a trimpot. All the values are preset at the factory to obtain minimum noise figure. Because of the pin-seal input rf connection, the helix operates at ground potential. Thus the cathode and anodes are all negative with respect to ground, and the operating voltage is required to be negative.

In addition to the operating voltage, a second dc voltage is required for the collector. The filament can be fed with either ac or dc. These voltage requirements are summarized below.

Voltage No.	Function	Nominal Value	Tolerance
1	Helix and anodes	- 200 vdc	± 0.5 v
2	Collector	+ 550 vdc	± 50 v
3	Filament	3 v, ac or dc	± 1 v

Filament current is nominally 0.6 amps. Each tube is supplied with a Final Data Sheet which specifies the exact value for that tube.



2851-1

Fig. 27 - Photograph of coupler designed to fit 3/4-inch capsule. The gun bulb, which has an O. D. of 0.55 inch, is held at the right end.

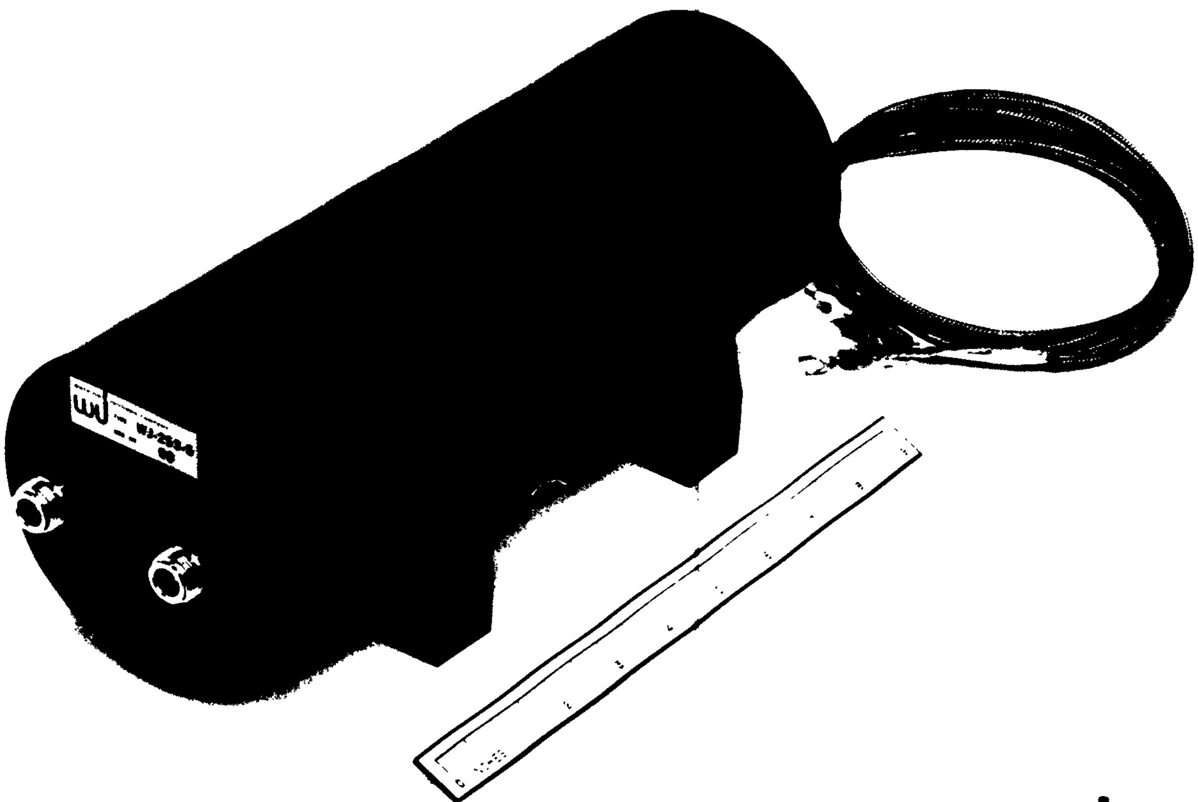


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Fig. 28 - Photograph of the WJ-253-5 low-noise amplifier.

D. RF Performance

1. Gain and Noise Figure

Performance of the three tubes delivered as end products on the contract is summarized on the Final Data Sheets included as Appendix I. The information presented there covers VSWR, gain, noise figure and saturation power output over the band 2.7 to 3.3 Gc. It should be noted that small-signal gain is substantially higher than the objective of 20 db, running on the average about 25 db. Noise figure is about one db higher than the 3 db objective. During the course of the program, experimental tubes yielded noise figure of 3.2 db, solenoid focused. The increase in noise experienced in going from solenoid to straight-field magnet is not more than two to three tenths of a db. Variations in helix attenuation, gun-to-helix alignment and cathode condition can account for about a half db from one tube to another. All noise figure measurements were made with a Hewlett-Packard Model 340B Noise Figure Meter, with the tube fed from a Hewlett-Packard Model S347A Noise Source. A calibrated 10 db attenuator was used between noise source and tube input.

Operation over a full octave bandwidth is entirely feasible with the WJ-253-5. Serial No. 27, for example, with helix and anode voltages optimized for wide-band operation yields noise figure of between 3.7 and 4.2 db, with gain of 24 db at mid-band, dropping to 21.5 db at 2 and 4 Gc.

2. Phase

Phase vs frequency for Serial No. 27 is shown in Fig. 29. This is a plot of incremental phase deviation of the amplifier as measured against a coaxial reference line of total phase length approximately equal to that of the tube. Consequently it includes phase errors due to connector mismatches in the reference path as well as in the path containing the tube. It will be noted that the deviation is less than ± 5 degrees over substantially the full band.

The objective specification with regard to phase was for stability of 5 degrees or less. As normally used, stability refers to incremental phase deviations or jitter at a given frequency as a result principally of voltage variations in the power supply. Phase sensitivity with respect to operating voltage (voltage No. 1) was measured on Serial No. 27.

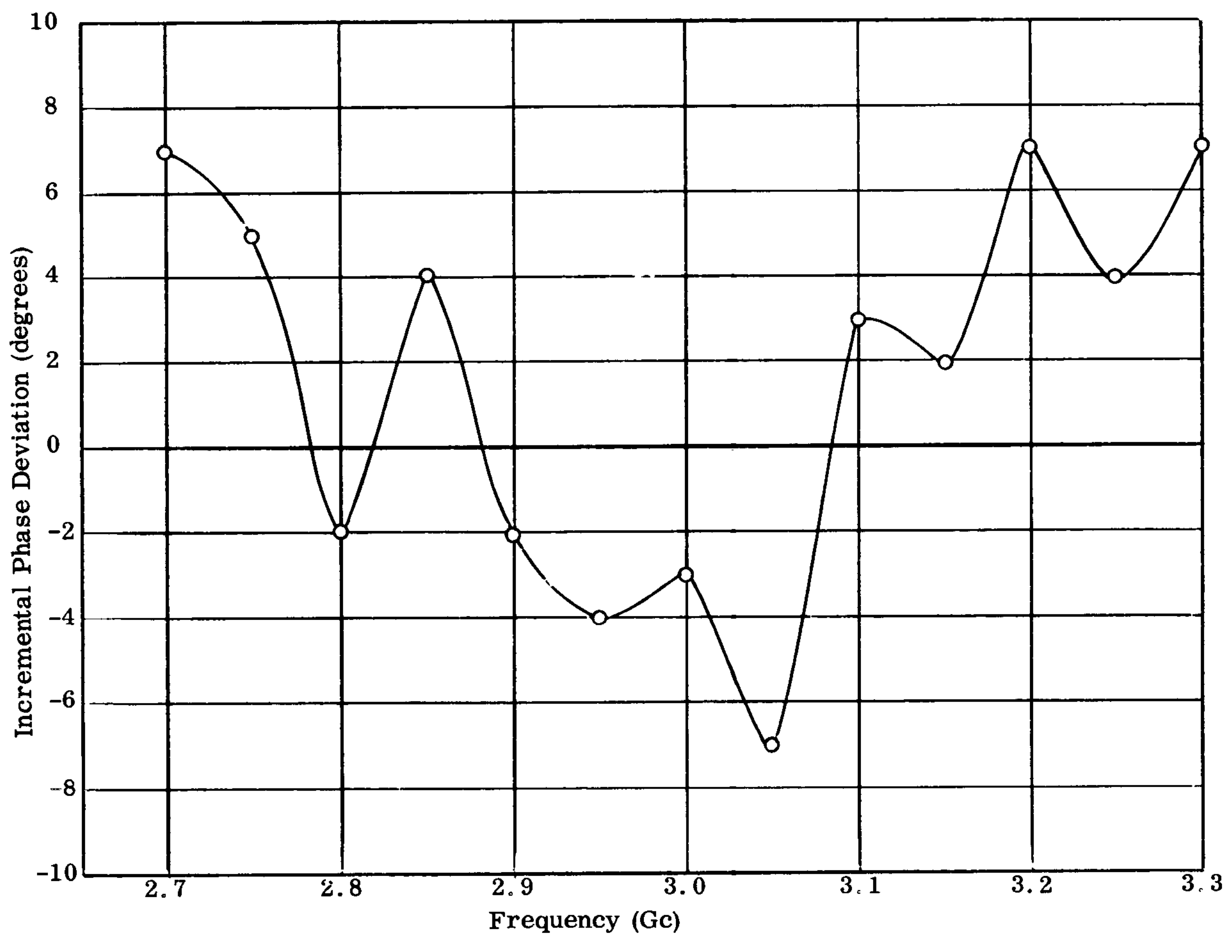

Fig. 29 - Incremental phase deviation of WJ-253-5, Serial No. 27, as measured against a coaxial line reference.

A change of one volt in the -200 volt supply produced a change in total amplifier phase length of 22.6 degrees. Thus, to maintain stability of ± 5 degrees in phase would require voltage stability of 0.22 volts, or approximately 0.1%. The corresponding sensitivity figure with respect to filament current is 120°/amp, at the operating current of 0.6 amp. Therefore, the filament current should be held to ± 0.04 amp, or ± 6.7 percent. In practice, it is not difficult to hold the filament current to a considerably closer tolerance than this.

CONCLUSIONS

Investigation of permanent-magnet focusing techniques for low-noise electron beams revealed advantages and weaknesses inherent in each method. Reversed-field focusing makes possible a weight reduction relative to straight-field focusing insofar as the magnet material only is concerned. Part of this advantage is lost due to the additional complexity of the structure required to initially adjust and hold the two magnets in proper alignment. In addition, the adjustment is quite critical. Higher helix voltage would render the adjustment less critical but at the same time would necessitate a longer helix in order to obtain the required total gain. Finally, the coupler structure is complicated by the requirement of a center-plane pole piece in order to minimize the reversal distance. For these reasons, it appears that reversed-field focusing is better suited to those applications where a beam voltage of at least several hundred volts is used, or where the magnetic field must be greater than 600 gauss. The latter situation would call for the use of either Alnico 8 or ferrite magnets, with an accompanying increase in magnet diameter.

PM-PPM focusing removes the restriction on tube length, which as a practical matter, must accompany straight-field focusing. Thus, if very high gain were desired in a low-noise tube, a PM-PPM structure would be of considerable benefit. The problem posed by using such a structure is basically one of achieving and holding the necessary critical adjustment between the two types of field. The assembly is necessarily more complex and therefore more costly than a simple straight field. It also is best suited to those applications where a helix voltage of several hundred volts is used. Otherwise, the field period in the periodic stack must be inconveniently small. For a number of reasons it has been found desirable to operate with low helix voltage. This leads to high gain per unit length, with a resultant suppression of helix-generated noise.

Straight-field focusing provides the nearest approximation to solenoid focusing and also results in the simplest magnetic circuit. The over-all package size is very little, if any, larger than would be required for a reversed-field assembly. Shielding of the type used in this application makes it possible to operate identical units side by side without mutual interference of the magnetic fields. In order to be practical, from the standpoint of size and weight, straight-field focusing is limited to the use of magnets less than approximately 8 inches long. The shielding problem becomes excessively difficult for longer magnets. Thus, high specific gain is needed in order to obtain over-all gain of around 25 db. This, in turn, favors low helix voltage. The straight-field magnet is the most economical of the three focusing systems investigated. Shielding and field straightening are readily accomplished, and focusing adjustments are reduced to a minimum.

Although temperature environment was not a consideration in this development, it should be pointed out that Alnico 5 does not experience the irreversible losses common to ferrite magnets subjected to temperature cycling. An operating temperature range of from -60°C to + 100°C is entirely feasible for a straight-field-focused amplifier of this type

On the units delivered as contract end products, small signal gain was about 4 to 6 db higher than the objective 20 db. Noise figure was about 4 db, or one db higher than the 3 db objective. The best tubes measured in the course of the program showed noise figure of about 3.2 to 3.4 db. Differences of around 0.5 db can occur as a result of variations in helix attenuation, gun-to-helix alignment, and the nature of the cathode coating and its surface condition.

As an over-all conclusion, it can be stated that this development program has resulted in the realization of a highly practical, compact, rugged low-noise amplifier. It combines the well-known advantages of an ultra-low-noise traveling-wave tube with a compactness and operational simplicity previously unobtainable. This should provide a considerably wider latitude to the system designer wishing to avail himself of the advantages afforded by the traveling-wave amplifier.

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APPENDIX I

FINAL DATA SHEETS FOR

TUBE TYPE WJ-253-5

SERIAL NUMBERS

25

27

31

FINAL DATA SHEET

LOW-NOISE TWT AMPLIFIER

The data as recorded below is the result of tests performed by our test department just prior to shipment of this tube, and is provided as a special service to our customers.

Tube Type WJ-253-5 Serial No. 25

Frequency (Gc)	VSWR Input	VSWR Output	Small Signal Gain (db)	Noise Figure (db)	Saturation Power Output (dbm)	
2.7		2.0	25.0	4.1	-3.0	
2.8			25.5	4.0		
2.9			26.0	4.1		
3.0			25.5	4.2	-4.4	
3.1			25.0	4.2		
3.2			25.0	4.2		
3.3	1.6		26.0	4.2	-3.9	

Tube Requirements

Pin No.		Voltage	Current
A & B	Heater	3.4 volts	.65 amps
D	Voltage 1 (negative)	-200 volts	5 ma
F	Ground	0	
C	Voltage 2 (collector)	550 volts	124 μa
E			
H			

Note: Voltage measured with respect to ground

Tested by: F. Mauch Date: 20 March 1963

WJ-116A

FINAL DATA SHEET

LOW-NOISE TWT AMPLIFIER

The data as recorded below is the result of tests performed by our test department just prior to shipment of this tube, and is provided as a special service to our customers.

Tube Type WJ-253-5 Serial No. 27

Frequency (Gc)	VSWR Input	VSWR Output	Small Signal Gain (db)	Noise Figure (db)	Saturation Power Output (dbm)	
2.7	1.7	1.4	24.0	4.2	-4.5	
2.8	1.7	1.2	24.0	3.9		
2.9	1.6	1.2	24.0	4.0		
3.0	1.7	1.3	23.0	4.0	-5.1	
3.1	1.7	1.4	24.0	4.1		
3.2	1.7	1.4	25.0	4.1		
3.3	1.3	1.4	25.0	4.2	-6.0	

Tube Requirements

Pin No.		Voltage	Current
A&B	Heater	3.0 volts	0.59 amps
D	Voltage 1 (negative)	200 volts	4.6 ma
F	Ground		
C	Voltage 2 (collector)	550 volts	109 μa
E			
H			

Note: Voltage measured with respect to ground

Tested by: F. Mauch Date 3/20/63

WJ-467

FINAL DATA SHEET

LOW-NOISE TWT AMPLIFIER

The data as recorded below is the result of tests performed by our test department just prior to shipment of this tube, and is provided as a special service to our customers.

Tube Type WJ-253-5 Serial No. 31

Frequency	VSWR. Input	VSWR. Output	Small Signal Gain (db)	Noise Figure (db)	Saturation Power Output (dbm)	
2.7	1.3	1.3	25.0	4.2	-4.	
2.8		1.3	25.0	4.1		
2.9			24.5	4.1		
3.0			24.5	4.1		
3.1			24.5	4.1		
3.2			24.0	4.1		
3.3			23.0	4.2	-6	

Tube Requirements

Pin No.		Voltage		Current	
A&B	Heater	3.2	volts	.61	amps
D	Voltage 1 (negative)	200	volts	5.5	ma
F	Ground				
C	Voltage 2 (collector)	550	volts	110	μa
E					
H					

Note: Voltage measured with respect to ground

Tested by: F. Mauch Date 4/5/63

WJ-467

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Unclassified report

Various methods of focusing a low-noise electron beam are described. Experimental results for reversed-field, combined straight and periodic fields, and shielded straight-field focusing are presented. Effective means for shielding a straight field magnet (over)

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